Wood Products and Carbon Storage:

Can Increased Production Help Solve the Climate Crisis?

Economic Analysis

SCIENCE FROM

THE WILDERNESS SOCIETY

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The Wilderness Society's mission is to protect wilderness and inspire Americans to care for wild places. Founded by prominent naturalists and biologists, including Robert Marshall and Aldo Leopold, the organization played an important role in helping pioneer science-based conservation advocacy and policy making. The Society remains dedicated to the concept that careful, credible science, combined with bold advocacy, and unswerving vision is the key to conservation success.

Headquartered in Washington, D.C., The Wilderness Society maintains twelve regional offices where our staff address on-the-ground conservation issues linked to local communities. Since spearheading passage of the seminal Wilderness Act in 1964, we have been a leading advocate for every major piece of Wilderness legislation enacted by Congress. Our effectiveness stems not only from our passion for protecting America's most special places, but also from the sound scientific research that underpins every aspect of our work.

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The Wilderness Society's Ecology and Economics Research Department (EERD) consists of experts in economics, ecology, and landscape analysis, including 12 Ph.D.-level scientists. This outstanding team provides the science to answer pressing questions about mineral exploration and development, forest and fire management, climate change, and many other issues affecting public lands. This information is key to understanding often complicated environmental issues, and ultimately making the right choices toward achieving lasting protection for the resources and places that sustain us and our ways of life. EERD provides science to inform not only The Wilderness Society's own conservation campaigns, but also the decisions being made by communities, land managers, legislators, and others about the future of America's wild places.

The Wilderness Society is a national non-profit organization and was founded in 1935.

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by

Ann Ingerson

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This science report is one of a series that stems from conservation research studies conducted by The Wilderness Society's Ecology and Economics Research Department. Other reports in the series that focus on similar issues include:

U.S. Forest Carbon and Climate Change: Controversies and Win-Win Policy Approaches; Economic Analysis, July 2007, Ingerson.

Measuring Forest Carbon: Strengths and Weaknesses of Available Tools; Science and Policy Brief, April 2008, Ingerson and Loya.

Environmental Benefits and Consequences of Biofuel Development in the United States; Science and Policy Brief, May 2007, DeLuca.

To get copies of these reports, visit wilderness.org or contact the Ecology and Economics Research Department at 202-833-2300.

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Foreword

Global discussions around climate change recognize the critical importance of maintaining land-based carbon sinks as part of a comprehensive policy to address this burgeoning crisis. Internationally, the first priority is to protect the tropical rainforests that are the true champions of carbon sequestration. Within the United States, the temperate rainforests of the Pacific Northwest and southeast Alaska serve as our own carbon storage champions. But other forests found across the country also play a significant role in the climate equation.

Experts predict, however, that without further protection, up to one million acres of U.S. forestland per year—along with much of their carbon—may be lost to development over the next fifty years. Yet rather than prioritize forest protection, much attention has been focused on the potential for wood products and wood fuels to store carbon or reduce fossil emissions. At its most extreme, this approach suggests that cutting down forests is the best preemptive move to prevent carbon losses due to fires or insect infestations. The tactic might work if 1) carbon was transferred, intact, and without any energy use, from the forest to its final resting place, 2) the carbon remained indefinitely locked away, and 3) a new forest immediately sprung up to replace the old one. The reality is, of course, a much more complex and very different scenario.

In The Wilderness Society's report, *Wood Products and Carbon Storage: Can Increased Production Help Solve the Climate Crisis?* author Ann Ingerson draws on a variety of sources to illuminate the greenhouse gas impacts of wood products and wood biomass fuels throughout their life-cycles. While detailed analyses are rare, the picture is complete enough to show the variability of the processing path followed by different types of trees in various parts of the country. Taking the entire life-cycle of these products into account, it becomes clear that an increased use of wood fuels and lumber will have very little net effect on climate change. To the contrary, the impact is as likely to be negative as positive.

Our report also takes a closer look at one particular policy mechanism, which could reward wood products carbon storage: the use of forest-carbon offsets in voluntary (market-based) or regulatory programs. Because such offsets are expected to balance emissions from other sources, it is important that the additional carbon sequestration be real. This document outlines several criteria for carbon offset standards to account for the full effects of harvested wood carbon.

Regardless of whether the greenhouse gas impacts of wood products and wood fuels are positive or negative, continuing to focus on these minor effects only distracts us from the larger task at hand. Our nation must transform an economy based on centuries of inexpensive fossil energy into one that will operate on a truly sustainable, renewable basis. The wood products industry can contribute to this goal by increasing processing efficiency, reducing energy use, extending product life, reusing and recycling wood materials, and promoting wood energy that is clean, efficient, and based on sound forest practices.

By implementing such transformative strategies and keeping America's forests as forests, the U.S. forestry community will make an invaluable contribution to mitigating climate change.

William H. Meadows
President

Spencer Phillips, Ph.D.
Vice President
Ecology & Economics Research Department

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"What's the use of a fine house if you haven't got a tolerable planet to put it on?"

— Henry David Thoreau, 1860

Key Points

1. When wood is removed from the forest, most of it is lost during processing. The amount lost varies tremendously by region, tree species and size, and local infrastructure.
2. The majority of long-term off-site wood carbon storage occurs in landfills, where decomposing wood gives off significant amounts of methane, a gas with high global warming potential.
3. In addition to wood processing losses, fossil fuels are required to turn raw logs into finished products and ship them from forest to mill to construction site to landfill.
4. Once wood losses and fossil emissions are accounted for, the process of harvesting wood and turning it into products may release more greenhouse gases than the emissions saved by storing carbon in products and landfills.
5. Biomass is often considered a "carbon-neutral" fuel, but its true climate impact depends upon management of the source forest and efficiency of use.
6. Under cap-and-trade programs designed to reduce greenhouse gas emissions, forest offsets are often proposed as a low-cost option for reducing atmospheric carbon dioxide, while providing abundant collateral benefits.
7. Wood products in use and especially in landfills do keep carbon out of the atmosphere, but proposals to assign credit for that carbon through offset projects require first solving a whole host of conundrums.
8. If wood products are credited in offset projects, project carbon accounting must reflect the characteristics of the unique processing chain followed by that project's logs.
9. Properly managed, wood can be a renewable source of building materials and fuels, but solving the climate crisis will require reducing the use of all materials and energy.

PHOTO BY EBBETS PASS FOREST WATCH

Removal of trees for processing into wood products affects carbon storage at every step — from the forest through processing to final disposal.

The Role of Forests in Addressing the Climate Crisis

PHOTO BY BOB KEEFER PHOTOGRAPHY/WWW.BKPIX.COM

Forested ecosystems, including soils, store more carbon than is currently present in the atmosphere. Old growth forests, like Willamette National Forest's Delta Grove shown above, are especially rich in carbon reserves.

Forest protection is a critical component of climate policy, both globally and within the United States. Forested ecosystems, including soils, store more carbon than is currently present in the atmosphere. In many places, these important reserves of carbon are threatened by forestland conversion or degradation. Globally, about 20% of recent anthropogenic greenhouse gas emissions can be traced to deforestation, a larger percentage of emissions than originates from the transportation sector. Continuing conversion of forests to other uses represents a significant climate threat that is well recognized by the public, the scientific community, and policy makers.

Beyond the broad consensus in favor of keeping forests as forests, however, when it comes to considering the best way to manage those forests, opinions diverge. The treatment of harvested wood as a carbon reservoir is particularly controversial. This report outlines the major issues surrounding carbon storage in harvested wood products, summarizing data from multiple sources. It also discusses the climate impacts of woody biomass fuels as an additional use for harvested wood. Because of intense interest in these topics, new research is constantly emerging that could modify the tentative conclusions reached here, but our hope is that the general framework will contribute to understanding of these complex issues.

Forest and wood product carbon accounting might be used to answer two related but distinct questions. First, what are the overall greenhouse gas (GHG) impacts of harvesting trees and converting them to wood products or burning them for fuel? Second, should climate policies encourage *increasing* timber harvest and wood products production to help *reduce* GHG emissions? Much controversy over the role of wood product carbon storage arises when these two distinct questions are tangled together, so we present them sequentially here.

The first question can be answered through life-cycle analysis, which is the subject of the first section of this report. This type of analysis seeks to understand the impacts of an activity "from cradle to grave," or in this case "from stump to dump." Life-cycle analysis raises inevitable questions about appropriate system boundaries and what effects are significant enough to measure. In addition, while tracking wood losses at each step is fairly simple, tracking fossil energy use and other GHG emissions associated with those steps is more complex. Moreover, tracking the indirect effects of wood use on the source forest and on markets for end-use products and alternative materials can twist the analyst in knots. Despite this complexity, however, the questions are essentially factual—what are the GHG flows associated with decisions to harvest timber for conversion to wood products or for burning to produce energy?

The second major question asked by this paper is more about policy choices than facts alone. Would increased wood products manufacturing be an effective and otherwise desirable approach to help mitigate global warming? Here the facts about whether GHG reductions *could* be achieved provide only a partial answer. Would changes have occurred anyway, without special incentives? What alternative actions might also achieve reductions? What secondary effects make each option more or less desirable? Choices about how to treat wood products and biomass as part of a GHG reduction strategy will ultimately affect land owners, loggers, nonhuman forest species from salamanders to redwoods, backcountry recreationists, wood product manufacturers and their employees, makers of wood substitutes, wood product consumers, etc. Policy choices require a complex balancing of interests to set public priorities.

Currently, a great deal of attention centers on carbon offsets as one policy mechanism that could influence carbon storage in forests and harvested wood. Under a cap-and-trade system, society chooses which sectors must comply with an emissions cap. In climate change mitigation policy, uncapped sectors often include agriculture and forestry, since their emissions are difficult to monitor and their lands often sequester more greenhouse gases than they release. Entities in these sectors may market GHG reductions or sequestration that are beyond "business as usual" to capped sectors as substitutes for required emissions reductions, or offsets. Since offsets under a cap-and-trade system derive their value from public policy, questions about the definition of "business as usual" and what counts as a saleable offset go beyond the technical and touch on public values, property rights, and equity. These complex issues associated with accounting for wood products carbon stores as part of forestry offset projects under a cap-and-trade climate policy are discussed in the second section of this report.

Carbon Losses and Energy Emissions Associated with Wood Products

Before following carbon through a wood products life cycle, it is important to understand the distinction between a greenhouse gas *inventory* and a *life-cycle analysis*. Inventories, like the U.S. Environmental Protection Agency (EPA) annual Inventory of U.S. Greenhouse Gas Emissions and Sinks, provide comprehensive measures of net greenhouse gas emissions across the economy as a whole, and may be useful to gauge the overall success of national or regional GHG-reduction efforts. Inventories are not particularly useful, however, in determining the GHG impacts of distinct parts of the economic system, because inventory information is divided into sectors with no indication of how one sector affects another. For example, carbon stored in wooden houses and landfilled wood is reported in the Land Use, Land Use Change, and Forestry sector of the EPA Inventory, while emissions from fossil fuels used to make, move, and dispose of those products are reported in the Energy sector, and emissions from decomposition at the landfill are reported in the Waste sector. For the same reasons, an inventory cannot assess the potential for one product to reduce overall emissions by substituting for a higher-emissions alternative. (One example of this type of question, the potential for wood products to lower GHG emissions by replacing concrete or steel, is treated later in this paper.) A life-cycle analysis, on the other hand, can illuminate the critical connections between sectors to predict the overall GHG impacts of a particular activity or policy.

A life-cycle analysis for wood products begins with the decision to harvest trees and ends with the disposal of wood products made from those trees. Two parallel and related streams of GHG impacts result *directly* from the harvesting, processing, use, and disposal of wood products. First, carbon is lost at each step of the processing chain due to the physical breakdown of wood, releasing carbon dioxide, methane, and other byproducts.[1] Second, the transportation of wood to mills, transformation into a variety of products, and delivery to customers and eventually to landfills requires energy, a large proportion of which is derived from fossil fuels. Gower (2003) clearly describes the importance of including these GHG fluxes in a wood products analysis:

> It is extremely important to note that almost all the forest product sequestration estimates are based on gross C accumulation. That is to say, GHG emissions from harvest, transportation of the roundwood or chips to processing plants (i.e., pulp and paper mills, sawmills), mill emissions, and transportation of the forest products to regional distributors and

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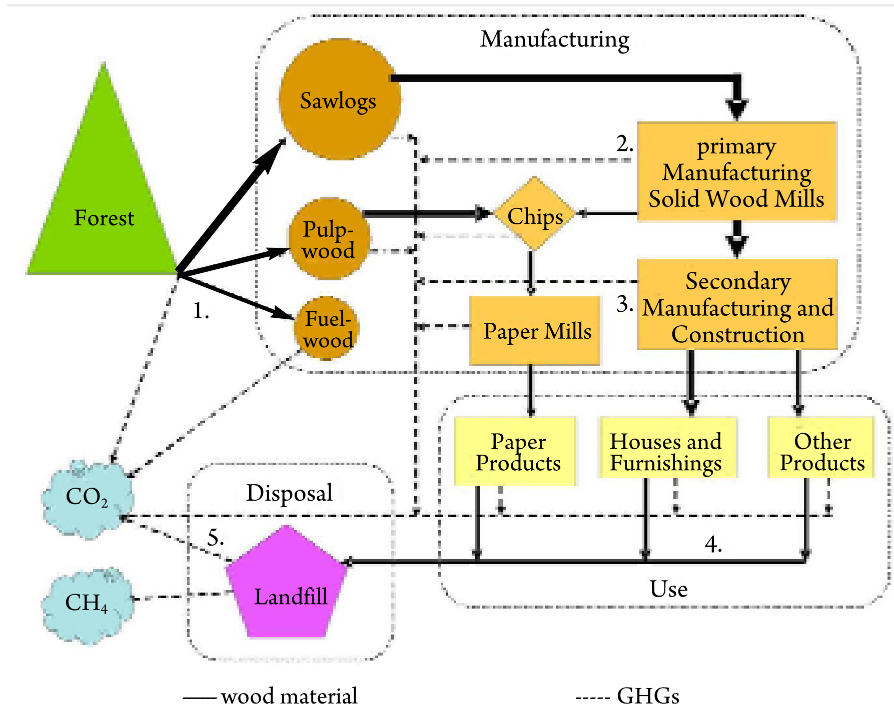
1 In the life-cycle analysis context, the wood products stream results in the release of a variety of different greenhouse gases in addition to carbon dioxide (CO_2) and they have varying effects on the climate. Methane, for instance, is produced from the anaerobic decomposition of landfilled wood. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Forster et al. 2007), methane (CH_4) is 25 times more potent than CO_2 as a greenhouse gas. (Many applications still use a global warming potential of 21, as suggested in the Second Assessment Report.) Climate policy makers have settled on "carbon dioxide-equivalents" (CO_2e) as a uniform unit for measuring the global warming potential of emissions—so, for example, 1 ton of methane would be measured as 25 tons of CO_2e.

consumers are ignored... Life cycle analysis (LCA)... can be used to quantify total GHG emissions for a forest product from cradle (i.e., forest establishment) to grave (i.e., final fate). Scientists have yet to demonstrate that there is a net C storage in forest products if a complete LCA, from cradle to grave, is completed.

Figure 1 illustrates the flows of materials and energy through the wood products processing chain. Table 1 summarizes the activities at each step that result in GHG emissions from either wood loss or fossil energy use. In addition to the direct effects of wood products production on greenhouse gas emissions, there are less well-defined, indirect effects on both the forest ecosystem and on economic activity that influence the overall GHG benefits of wood products. These are sketched out under the section on Broader System Effects below. Biomass fuel is a special type of wood product, the climate benefits of which depend upon replacing fossil fuels rather than increasing carbon storage. Because of this fundamental difference, the greenhouse gas implications of increasing biomass fuel use are also treated in a separate section.

FIGURE 1.

The Wood Products Processing Chain



Wood Carbon Losses Through the Processing Chain

This section outlines how carbon stored in wood is lost through decomposition or combustion during five stages of processing

TABLE 1.

Wood Harvesting and Processing Steps

Step	Activities
1. Harvest	Road construction; felling, limbing, cutting trees to length; transport to landing and mill
2. Primary processing	Sorting out material used for fuelwood and paper; sawing into lumber, planing; manufacture of plywood and other panels
3. Secondary processing and construction	Manufacture of primary products into end products (furniture, cabinets, flooring, windows and doors); building construction
4. Use	Maintenance and repairs
5. Disposal	Landfilling, dumping, burning; recovery for re-use

as illustrated by the dotted lines in Figure 1: (1) harvest site losses, (2) primary processing mill residues, (3) secondary processing and construction waste, (4) product use and maintenance, and (5) ultimate disposal.[2]

Studies present wood losses and GHG emissions in varying units, and percentages use different bases. Since the alternative to harvesting trees would be to leave them standing, in this report we express losses at each step in the processing chain as a percentage of carbon in the standing tree. We assume that carbon density in wood products is similar to that in the live tree, so that losses in wood volume provide rough estimates of carbon losses at each step.

Timber harvests usually produce a mix of roundwood types (logs, pulp, fuelwood, etc.), and a GHG accounting of the effects of harvest decisions should reflect the impacts of the entire bundle of products. However, since carbon storage benefits rest with long-lived wood products, and paper is widely acknowledged to be a net emitter of greenhouse gases,[3] we focus here primarily on solid wood products.

Due to the complexity of wood markets, with multiple end products and variable recapture of byproducts and raw materials, generalizations about carbon losses are risky. Nonetheless, broad guidelines for estimating the loss of wood carbon during timber processing are provided by the U.S. Forest Service, in a reference (Smith et al. 2006) used for the U.S. Department of Energy's voluntary GHG registry known as the 1605(b) program. This reference uses available data from mill surveys, forest inventories, forest products research, and data on landfills and housing stock, among other sources, to estimate wood product carbon and predict losses over time as products are disposed of and decomposed. Due to data limitations, these estimates are necessarily based on broad regional averages and extrapolation from knowns to unknowns.

To supplement this general information, some additional research results are summarized below. Our analysis finds losses of similar magnitude to the estimates in Smith et al. (2006). The data that we synthesized from multiple studies indicate that as little as 1% of the carbon present in the standing tree may remain in solid wood products in use after 100 years. Interestingly, landfills make a much larger contribution to long-term carbon storage, sequestering perhaps 13% of the carbon originally present in the standing tree. Table 2 and Figure 2 illustrate the range of wood losses through the processing chain and after 100 years in use, with detailed explanations to follow.

As little as 1% of the carbon present in the standing tree may remain in solid wood products in use after 100 years. Interestingly, landfills make a much larger contribution to long-term carbon storage.

[2] This system boundary excludes several less direct effects of wood harvesting activities, including the longer-term impacts of wood harvest on forest carbon, the impacts of wood fuels on fossil fuel consumption, and possible substitution of wood for materials that have different manufacturing emissions. These effects are treated, albeit briefly, in the Broader System Effects and Biomass sections below. Our approach also assumes that impacts will be similar for wood products utilized within the U.S. and those that are exported, so that the location of the impacts is irrelevant to GHG assessments.

[3] High-lignin papers may remain in landfills for considerable time, but the methane released from the breakdown of landfilled paper and the energy required for paper production outweigh any carbon storage benefit. The assumption that paper production contributes little on balance to mitigating GHG emissions could change if a greater percentage of paper were recycled or if more of the methane generated by landfilled paper were captured for energy generation.

TABLE 2.

Reductions in Wood Available for Long-Lived Wood Products

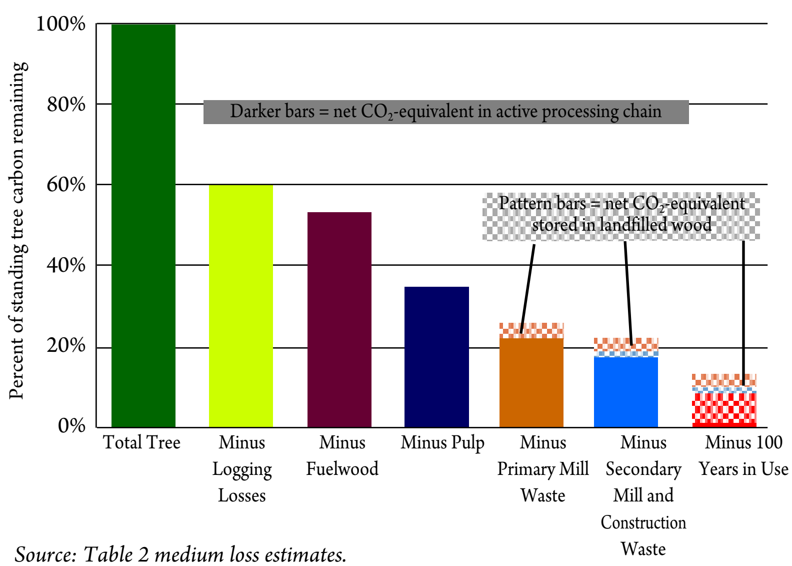
(% of Live-Tree Volume)

Processing Step	Low	Medium	High
1. Harvest	22%	40%	59%
2. Primary processing – fuelwood portion	2%	5%	33%
2. Primary processing – pulp portion	3%	19%	30%
2. Primary processing – mill	4%	13%	22%
3. Secondary processing	6%	5%[4]	18%
3. Construction	1%		5%
4. 100 years in use	14%	17%	19%
Cumulative losses		99%	

Sources: See text.[5]

FIGURE 2.

Carbon Storage Through the Wood Products Chain



Source: Table 2 medium loss estimates.

It is important to recognize that the wood from a single tree may experience high losses at one stage and very low losses at another. The variety of processing paths a log may follow, as well as the variation in losses at each processing step, illustrates why direct sampling of wood flows would be important to understand GHG emissions from wood losses. Still, the fact remains that even the most efficient processing chain will result in the loss and emission of a significant portion of the carbon present in the standing tree.

1. Harvest

Significant amounts of carbon are lost during timber harvest when the un-merchantable portion of the tree is piled and burned, left in the woods or at a landing to decompose, or collected and burned as biomass energy. Both the amount and the rate of this loss affect accounting for carbon emissions. Zhang et al. (2008) surveyed data from 110 research sites and found median litter decomposition half-lives between 2 and 3 years.[6]* Given such rapid decomposition rates, many studies make a simplifying assumption that logging residue is lost immediately, whether burned or left to decompose.

The U.S. Forest Service (2008) estimates logging residue at 30% of roundwood volume for the United States as a whole. State-level percentages range from 3% to 84% (U.S. Forest Service 2007).[7] These percentages fail to capture the total carbon losses during

4 Secondary processing and construction losses are not cumulative—the highest secondary processing losses occur in industries like furniture, where construction losses are zero. The estimate for medium losses from secondary processing and construction combined assumes 76% of solid wood is used in construction and 24% in finished products, based on data from Smith et al. 2006, Table D2 (see Data Appendix for further details).

5 Low and high estimates are from different analyses or regions. Medium estimate is national average (for harvest losses, fuelwood, and pulp), simple average of low and high estimates (for primary processing – mill and in-use), or weighted average (for secondary processing and construction, based on national proportion of wood used for construction and other long-lived uses).

6 *Many of the factors reported here required combining multiple sources of data, using different units or a different base for percentages. To avoid cluttering the text with computational details, we have explained all these computations in a Data Appendix. Items explained in the Data Appendix are marked * in text.

logging, as reported logging residue volumes exclude roots, stumps, and small limbs.[8] Including stumps and small limbs would increase logging residue volumes by an average of 14% for softwoods and 24% for hardwoods (McKeever and Falk 2004), which would increase overall national average residue to about 36%* of roundwood volume. Large roots range from 5% to 51% of total tree biomass, with a mean of 19%, in cold temperate and boreal forests in the United States (Li et al. 2003). Taking all these factors together, approximately 40%* of the original tree volume, with a range from 22%* to 59%* for individual states, might be left behind at harvest, and its stored carbon lost.

Actual losses would vary significantly depending on the type of harvest (whole-tree or bole-only, commercial thinning or diameter-limit or clearcut) and the type and quality of timber (hardwoods generally produce more residue than softwoods, and higher-quality trees produce proportionally less residue). A portion of in-forest decomposition losses due to logging might occur even without harvest activity, due to natural tree mortality. An increase in the commercially used portion of the tree would lower logging residue losses, but might also ultimately reduce site productivity.

2. Primary Processing

As we have seen in the discussion above, logs removed from a harvest site represent approximately 60% of the volume—and hence, stored carbon—of the trees from which they came. Harvested logs may be destined for pulp, fuelwood, sawlogs, or other specialized uses, but long-term carbon storage benefits come mainly from the sawlog portion. The portion of wood going to each use varies widely by region, and will also differ among harvest operations within a region, but the following calculations provide a general indication of processing losses:

- According to figures in a recent Resources Planning Act assessment (U.S. Forest Service 2008), fuelwood removals in 2007 ranged from 3% (in the South Central region) to 51% (Rocky Mountain region) of total roundwood removals by volume, with a national average of 9%.[9] This national average amounts to about 5%* of the original standing

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7 Roundwood is the volume of material loaded onto a truck for processing into lumber, pulp, fuelwood, or other uses. Timber Product Output data are from mill surveys and field sampling at logging sites. Data are imputed for years between surveys and could fail to reflect recent changes in technology.

8 Logging residue also excludes wood lost during pre-commercial thinning or land clearing, about 8% of total material removed from forests nationwide, but since these losses are not directly related to a harvest decision we consider them outside the boundary of our life-cycle analysis.

9 Most of the Forest Service data cited in this report groups U.S. states into nine regions as follows: Northeast (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and West Virginia); North Central (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin); Southeast (Florida, Georgia, North Carolina, South Carolina, and Virginia); South Central (Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Oklahoma, Tennessee, and Texas); Great Plains (Kansas, Nebraska, North Dakota, and South Dakota); Intermountain (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming); Alaska; Pacific Northwest (Oregon and Washington, further split into Westside and Eastside in some reports); and Pacific Southwest (California and Hawaii).

tree volume burned as fuelwood, leaving 55% (60% minus 5%) available for other uses.[10]

- The portion of total roundwood volume used for pulp ranges from 6% for hardwood sawlogs in the North Central region to 50% for softwood pulp in the Pacific Northwest Westside, with a national average of about 31%* (Smith et al. 2006, Table D6).[11] These pulp diversions amount to another 3%* to 30%* by region of original standing tree volume lost from the long-lived products stream, with a national average of 19%*. This leaves about 36% (55% minus 19%) of the original tree volume available for processing into long-lived products.
- Bark accounts for about 15% to 18% of roundwood volume (Smith et al. 2006, Table 5). Most is burned for fuel, with small amounts used for mulch, other short-term uses, or discarded. The bark portion of the 36% of original tree volume remaining after fuelwood and pulp are sorted out would amount to another 6%* of original tree volume. However, making a conservative assumption that sawmill waste percentages, as well as fuelwood and pulp diverted, include this bark waste, we will not consider bark as an additional loss in the volume of wood available for processing into long-lived products.

Once wood destined for short-lived uses (fuel and pulp) has been removed from the solid wood stream, further losses during primary processing will vary considerably depending on the product and the equipment used. Standard circular sawmills may convert only 50% of a log into lumber, while thin-kerf bandsaw mills may approach 70% conversion efficiency. Oriented strandboard (OSB), medium-density fiberboard (MDF), and particleboard may approach 90% conversion of non-bark wood to panels (at the cost of increased use of energy and resins—see the section on fossil energy emissions below). Northeastern sawmills producing hardwood lumber averaged 56% loss of wood from log to planed lumber (Bergman and Bowe 2008). The Consortium for Research on Renewable Industrial Materials (CORRIM) estimated wood waste losses during primary solid wood

PHOTO COURTESY OF THE MANNING AND AREA ECONOMIC DEVELOPMENT SOCIETY, ALBERTA, CANADA

Either at the harvest site landing or at the mill, logs are sorted by quality and diameter into smaller material used for fuelwood or pulp (relatively short-lived uses) and large material suitable for sawing into lumber.

[10] Wood fuels are often considered "carbon-neutral," but when evaluating the potential for long-term carbon storage in harvested wood, burning must be treated like any other wood loss because it definitely accelerates the release of carbon. However, see the Biomass section below for a discussion of possible carbon benefits of fuel substitution. Processing byproducts used for fuel are not included in these fuelwood percentages, however, since carbon losses from this source would be included as part of processing waste.

[11] Additional waste material from solid wood processing may also be recovered to make paper, but because of paper's emissions profile this recovery would not make a significant contribution to carbon storage.

processing ranging from 26%* (for Southeast OSB) to 58%* (for Southeast softwood lumber) of the raw log (Kline 2005; Milota et al. 2005; Wilson and Sakimoto 2005). A study from Finland estimated 56% losses for softwood lumber and 62% for plywood (Liski et al. 2001).[12] With about 36% of original standing tree volume available for processing into long-lived products, primary mill losses amount to about 4%* to 22%* (average of 13%) of the standing tree volume, leaving about 23% of the original volume to be incorporated into long-lived wood products such as lumber or panels.

3. Secondary Processing and Construction

Once primary products leave the mill, many undergo further processing into finished products, sometimes in multiple stages. For instance, lumber might be shaped for molding or flooring, then further trimmed at the construction site. Systematic studies of wood waste during secondary processing are hard to come by, but a few examples indicate the general magnitude of waste at this step.

Losses in furniture and cabinetry are particularly high due to trimming of knots and other defects. A North Carolina study (Wood Waste and Furniture Emissions Task Force 1998) assumed wood waste in furniture manufacturing at 55% to 65% of lumber. A Georgia furniture manufacturer scrapped approximately 40% of all hardwood lumber purchased due to cracks and other defects (Crumpler 1996). A British study (BFM, Ltd. 2003) found secondary manufacturing waste at 20% of raw material purchased for "board" products (MDF, OSB, plywood), 27% for softwood lumber, 37% for hardwood lumber, and 50% to 80% for veneer. This range of secondary processing losses (expressed above as percentages of lumber or panel volume) translates to losses of 6%* to 18%* of original standing tree volume lost at the secondary manufacturing stage.

Wood destined for furniture, cabinetry, windows, and doors experiences most losses at the secondary manufacturing plant. By contrast, framing lumber, flooring, paneling, and siding undergo further trimming at the construction site. Using wood waste amounts reported by the National Association of Home Builders (NAHB) Research Center (1995) and total wood materials required for construction of a 2,082-square-foot single-family house (NAHB, cited in Wilson and Boehland 2005) we estimate that construction-site waste in home building ranges from 4% for solid wood to 10% for engineered wood components. The general magnitude of construction wastes according to NAHB data is similar to the 10%-12% range found in several other studies (Cornell University Cooperative Extension 1996; James et al. 2007; McKeever and Falk 2004). Particular construction applications will naturally diverge from these overall national averages. A Cornell University study of the construction of seven homes (Cornell University Cooperative Extension 1996) found wood waste per square foot of home varied from one-half to twice the NAHB estimates cited above. A Texas study found that construction wood waste from large, custom-built homes was approximately three times the NAHB amounts recorded for

[12] Mill residues from primary mills may be burned on-site for energy, used to make pelleted wood fuel, converted to structural panels or paper, or dumped or landfilled. Other than structural panels and discards in an anaerobic landfill, the other possible uses for mill residues would store carbon for very short time periods so they are considered direct losses here.

smaller homes (Houston Advanced Research Center 2005). This range of construction site losses (expressed above as percentages of lumber volume) translates to losses of 1%* to 5%* of original standing tree volume.

Generally the same wood material will not be subject to secondary processing losses and construction site losses, as most construction materials undergo primary processing only. Assuming that 76%* of wood volume in long-lived products is construction lumber, with the remaining 24% in furniture, cabinetry, and other products, total secondary processing and construction losses might be about 5%* of original standing tree volume. If 23% of the tree remains after primary processing, this leaves about 18% of original live tree volume actually incorporated into long-lived products.

4. Use

Even when mills turn out a product like lumber that is capable of storing carbon for long periods, actual long-term carbon storage will depend upon its final use and expected lifetime in that use.

Once products are placed in service, carbon losses begin to occur as products, or portions of them, are disposed of. Even when mills turn out a product like lumber that is capable of storing carbon for long periods, actual long-term carbon storage will depend upon its final use and expected lifetime in that use, as well as whether it is discarded prematurely due to renovations and repairs. Lifetimes in use vary widely among solid wood products. The longest-lived uses are for buildings or furniture, and about 60%* of all primary solid wood products (lumber and paneling) find their way into these uses (Smith et al. 2006). Shorter-lived uses include pallets and other shipping containers and miscellaneous manufacturing (e.g., matches, popsicle sticks, toothpicks).

Half-lives are generally used to indicate the rate at which wood products will be discarded over time.[13] The latest WoodCarbII model, used for the 2007 Inventory of U.S. Greenhouse Gas Emissions and Sinks, assumes half-lives of 86 years for single-family and 52 years for multi-family homes built recently (these half-lives are shorter for earlier construction years), 26 years for residential repairs, 38 years for "other" solid wood uses, and 2.5 years for paper (Skog 2008). These half-lives were calibrated so that the WoodCarbII model estimates of discards to landfills match EPA solid waste estimates for 1990 to 2001, and estimates of wood carbon in housing in 2001 fit with Census of Housing data.

Beyond half-lives, estimates of wood carbon remaining in use also depend upon the equation used to describe the disposal path. Researchers make various assumptions about whether the disposal path is linear, logarithmic, or follows some other pattern. Miner (2006) provides examples from Europe (European Forest Institute - EFI), Japan (National Institute of Environmental Studies - NIES), Canada (Kurtz), and alternative U.S. approaches, that can be compared to the first-order functions used in tables developed for Smith et al. (2006) and the 1605(b) program. Figure 3 compares different curves describing the percentage of original tree carbon that remains stored in wood products over time (initial stores begin at 18% since that is the approximate amount of the carbon in the standing tree that would be incorporated in solid wood products). This figure shows that, depending on the underlying assumptions about curve

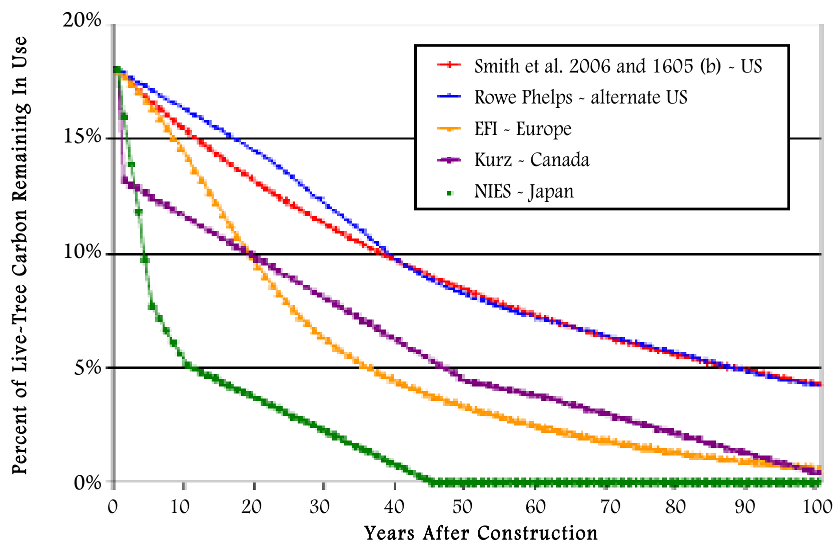
[13] For 1,000 tons of lumber used to construct homes in the year 2000, a 100-year half-life implies that 500 tons will remain in use in the year 2100.

formulas and use lives, estimates of carbon still in use in year 100 range from 0% to 4.6% of the carbon originally present in the standing tree. Based on this comparison, the assumptions behind U.S. use curves appear to be less conservative (i.e., result in a higher estimate of 100-year carbon) than those of some other countries.

FIGURE 3.

Estimates of Carbon Stored in Wood Products Over Time

(% of Total Carbon in Standing Tree)



Sources: McKeever 2002; Miner 2006; Smith et al. 2006; Skog 2008.

***Renovations*:** Even before long-lived products reach the end of their expected lifetime, users will discard portions as they repair and renovate homes and furniture. Systematic data are lacking on the percentage of wood products that are discarded before the end of their useful lives, but a few statistics indicate that this is likely to be a significant source of wood carbon losses. Residential repairs and renovations utilized 61% as much lumber, 42% as many square feet of structural panels, and 60% as many square feet of nonstructural panels, as new construction in the United States in 1998 (McKeever 2002). Renovations generate about 20% of all wood waste, more than the percentage of wood waste from new construction (McKeever and Falk 2004).

In the WoodCarbII model, half-lives for houses and wood used for repairs are calibrated so that model estimates of wood discarded to landfills match EPA data on discards from 1990 to 2001. Hence, in a general sense the calibrated half-lives for houses incorporate the effects of wood discarded during renovations, but additional analysis would be needed to sort out the separate effects of renovation waste and expected house lifetimes.

5. Disposal

The percentage of harvested wood in use as long-lived products does not tell the whole story of wood products carbon sequestration. In fact, discarded wood in landfills actually stores much more carbon than the wood in long-lived products in use. In addition to discarded products, some of the wood waste from mills and construction sites will also be disposed of in landfills (checkered bars in Figure 2). Wood carbon in landfills can persist for some time, as anaerobic conditions inhibit the fungi that specialize in breaking down lignin (the substance that makes wood "woody"), but landfill decomposition rates vary considerably with environmental and management factors. Predicted decomposition rates are often extrapolated from laboratory experiments (Barlaz 1997) that were designed to calculate maximum methane emissions under anaerobic conditions. These studies may overstate total decomposition under

PHOTO BY PHILIP ARAMAN, USDA FOREST SERVICE

Wood discarded in landfills continues to store carbon for some time once it is buried and cut off from an oxygen supply. The portion that does decompose releases significant quantities of methane, however, which has a much higher global warming effect than carbon dioxide.

field conditions, but they are also short in duration which makes extrapolation to 100 years quite speculative.

Field tests near Sydney, Australia, confirm that solid wood may last for a significant time in landfills (Ximenes et al. 2008). Researchers estimated carbon losses based on the proportion of lignin in excavated wood that was buried for 19, 29, and 46 years (assuming lignin totally resists decomposition under anaerobic conditions). Wood buried for shorter periods appeared to decompose very little, while an estimated 17%-18% of initial wood carbon had been released from the 46-year sample. Results from these three sample sites raise as many questions as they answer. After year 46, would decomposition continue at an accelerated rate due to removal of some initial deterrent to bacterial activity? Or would decomposition slow as lignin constitutes a larger proportion of the residual material? Similar to the case discussed above regarding wood products in use, the form of the equation that is chosen to describe landfill decay also has significant implications for stored carbon estimates at any given time (Pingoud and Wagner 2006). Various studies have assumed that anywhere between 20% and 80% of landfilled wood is subject to decay (Borjesson and Gustavsson 2000). Only further research can answer these questions, and variable landfill conditions mean that estimates will always remain uncertain.

The WoodCarbII model assumes that only 56% of paper and 23% of solid wood are subject to decay in landfills, with decay half-lives of 14.5 years for paper and 29 years for wood (Skog 2008). These numbers were calibrated to match solid waste estimates from the EPA and to meet IPCC guidelines. WoodCarbII also makes assumptions about how much of the waste at each stage will be landfilled, burned, dumped, or recycled and how quickly its carbon will be released as a greenhouse gas (Skog 2008). Based on this model, the 1605(b) tables (Smith et al. 2006, Table 6) indicate that about 9% of North Central region softwood pulp volume (or about 5%* of standing tree volume) would remain in use or in landfills at 100 years, with over 91% of that in landfills. At the other end of the scale, the tables estimate that 41% of Pacific Northwest Westside softwood sawlog volume (or about 25%* of standing tree volume) would remain in use or in landfills at 100 years, with two-thirds of that in landfills. Clearly, what happens in landfills is an important part of wood carbon accounting.

Methane: Many carbon accounting schemes address only the *rate* at which carbon is released from decomposing products, without accounting for the *form* in which it is released, but the global warming potential of methane (CH_4) is 25 times that of CO_2. Due to the anaerobic conditions, over half the carbon released from decomposing wood in landfills will be in the form of methane, or about 20% once flaring or burning for energy use (which converts CH_4 to CO_2) is accounted for (U.S. EPA 2006). A Swedish study (Borjesson and Gustavson 2000) found that if all wood from the demolition of a four-story wood-frame apartment building is landfilled at the end of useful life, rather than being burned or re-used, the consequent methane emissions are large enough to make the overall structure a strong net emitter of greenhouse gases over its complete life cycle.

If 23% of the mass of landfilled solid wood products eventually decomposes, and 20% of the carbon thus emitted is released as methane, the global warming potential of these emissions would be about 60%* of the CO_2e originally stored in the discarded wood. The 1605(b) tables, based on carbon alone, do not reflect this methane effect. Because of methane's climate impacts, landfilled wood waste from mills, construction sites, and house demolition stores only about 13% of the CO_2e present in the standing-tree (checkered bars in Figure 2). Including the carbon remaining in wood products in use (solid bars in Figure 2), total harvested wood CO_2e at 100 years is about 14% of that present in the standing tree.

Fossil Fuel and Other GHG Emissions Associated with Wood Products

In addition to the carbon lost through decomposition or combustion of wood waste, the processing and transport of wood products also requires energy, much of it provided by fossil fuels that emit greenhouse gases when burned. Returning to Figure 1 (page 4), energy emissions are associated with transformations that occur within the solid shapes in the diagram, as well as with the transportation represented by solid lines. Few full life-cycle assessments have been made of energy use and carbon emissions associated with wood products from harvest to disposal. Nonetheless, several sources indicate that energy use and other emissions associated with these stages can be substantial, perhaps even greater than the CO_2-equivalent stored in the finished wood products.

Since paper is known to be an energy-intensive net emitter of greenhouses gases, we concentrate here, as above, on the solid wood products chain. Carbon losses from combustion of wood as fuel (both wood sorted as fuelwood and processing byproducts burned for energy) have already been included as losses to the long-lived products stream in the previous section, so this section considers only fossil fuel energy emissions. Again, we use wood carbon remaining in use or in landfills at 100 years after harvest as the metric to represent the carbon storage benefits of wood products. The emissions associated with producing those benefits are the GHG cost of that activity. Therefore, this section expresses GHG emissions from energy use during processing, transport, use, and disposal of wood products as a ratio to 1 metric ton CO_2e of 100-year wood carbon.[14]

1. Harvest

Harvest-related activities at the source forest emit a relatively small amount of greenhouse gases. A CORRIM study (Johnson et al. 2005) found emissions from

[14] This section assumes that 100-year wood carbon (including landfilled wood) would be approximately 14% of standing tree carbon. See Data Appendix for computations marked by * in text.

fossil fuels used in harvest, replanting, and fertilization—plus methane and nitrous oxide (N_2O, a greenhouse gas more than 300 times more potent then CO_2)—of about 0.9%* to 1.3%* of CO_2e in the raw log. In a life-cycle analysis for Chetwynd Forest in British Columbia, Gower et al. (2006) estimated that harvest-related emissions (including road-building, reforestation, and transport to the sawmill) were about 2%* of the CO_2e stored in the roundwood removed. When compared to long-term carbon storage rather than raw logs, the ratio of harvest-related emissions to 100-year carbon ranges from about 0.04* to 0.07*.

2. Primary Processing

CORRIM studies found fossil fuel-related emissions for processing of four primary wood products ranging from 2%* (softwood lumber, including only on-site emissions) to 18%* (oriented strandboard, including off-site emissions) of the CO_2e in the raw log (Kline 2005; Milota et al. 2005; Wilson and Sakimoto 2005). Data from Finland indicate primary processing emissions range from 3% to 7% of log CO_2e content (Liski et al. 2001). Gower et al. (2006) found sawmill emissions from nonrenewable energy to be 2%* of the CO_2e in the raw log for softwood lumber. Bergman and Bowe (2008) found that processing of hardwood logs resulted in fossil fuel-based GHG emissions equivalent to 2%* of the initial log carbon (for on-site emissions only) or 7%* (including off-site). Skog et al. (2008) estimate that GHG emissions associated with resins and other non-wood components of panels are as high as 20%* of the CO_2e stored in the panel (a factor that likely accounts for some of the high off-site emissions for oriented strandboard above).

Beyond on-site process energy and transport of raw materials to the manufacturing facility, transport from mill to retail outlet can contribute significant emissions.

Beyond on-site process energy and transport of raw materials to the manufacturing facility, transport from mill to retail outlet can contribute significant emissions. The U.S. EPA (2006) provides life-cycle data that combine manufacturing and transport emissions for selected wood-based products. Emissions from burning of biomass to produce process energy are not included. The EPA's transport emissions include only the shipping of raw materials to the place of manufacture (assumed to be 20 miles) and from there to the retailer; they exclude transport to the final consumer and do not account for any CH_4 or N_2O emissions from transport. Raw material acquisition and manufacturing and transport emissions (in metric tons of carbon equivalent per wet ton of material arriving at the landfill) amount to 0.05 for lumber and 0.10 for medium-density fiberboard (U.S. EPA 2006). This translates to emissions of 12%* to 24%* of the CO_2e content of these raw materials.

Gower et al. (2006) tracked transport emissions as wood products moved from sawmill to retail store, and found that this stage by far dominated the overall emissions picture at about 70% of the CO_2e stored in the lumber. The market chain for this lumber included transport to Home Depot wholesale warehouses, with redistribution across the continent; the significance of transport emissions for this processing chain illustrates the importance of sampling emissions flows for each individual offset project. At the other end of the transport spectrum, analysis by CORRIM of two sample wood-framed houses, a 2,062-square-foot house in Minneapolis and a 2,153-square-foot house in Atlanta, found transport from manufacturing facility to construction site to be an insignificant source of emissions (Meil et al. 2004).

PHOTO BY DAVID BRIGGS, PROVIDED BY RURAL TECHNOLOGY INSTITUTE

Construction emissions are typically calculated for the building frame only, without factoring in the GHG costs of turning raw wood material into paneling, cabinets, finished flooring, and other components.

Based on the studies above, the ratio of primary processing emissions to 100-year carbon stores varies from about 0.02* to 0.77* for processing and related raw material transport. If transportation of the finished product to outlets is included, the ratio varies from 0.16* (EPA 2006) to 1.19* (Gower et al. 2006; 1.12 for transport and 0.07 for primary processing). Since finished product transport emissions are so variable (from 0 for products that are used very close to the manufacturing site, to the dominant element of the emissions picture for those with continent-wide transport networks), we have reported this emissions source separately in Table 3 and Figure 4 below.

3. Secondary Processing and Construction

Manufacturing of lumber or panels into secondary products (windows, doors, cabinets, furniture) and/or construction into buildings requires additional energy. The studies cited above provide emissions data only through primary processing. With very little comprehensive data available, our accounting for wood products emissions includes a potentially large gap for energy emissions from secondary processing.

CORRIM studies calculated construction emissions for the two sample wood-framed houses described above. These homes stored a total of 22.4 and 17.1 metric tons of CO_2e, respectively, in their wood components (Perez-Garcia et al. 2005) over an expected lifetime of 75 years. These studies included only basic framing, and therefore did not account for secondary processing or construction emissions associated with components such as finished flooring, cabinets, wood paneling, wooden doors, and so on. Thus, total emissions from actual home construction would be much higher than those reported here. In the CORRIM studies, fossil fuel GHG emissions from construction were 1.3 and 1.1 metric tons CO_2e, respectively (Meil et al. 2004), but only a portion of those emissions were directly associated with wood components. With wood at 15% of materials for the Minneapolis house and 10% for the Atlanta house, the ratios of construction emissions to 100-year carbon stores associated with wood products might be about 0.011* and 0.008*.

It is important to recognize that total manufacturing and construction emissions for these sample homes far exceed the CO_2e stored in the wood, even without considering secondary processing of the wood components. For the Minneapolis house, emissions are 1.65 times the CO_2e content of the wood components, and for the Atlanta house 1.25 times. The entire home must be built in order to store the wood long-term, but it is not clear what portion of total emissions should be considered a direct cost of wood carbon storage.

4. Use (Maintenance)

Since wood products would not be long-lived without maintenance and heating of the homes and furniture that store the wood, some accounting for maintenance energy is appropriate. Heating and cooling for the two CORRIM model houses emitted 5,174 kg of CO_2e (Minneapolis) and 3,032 kg of CO_2e (Atlanta) per year (Winistorfer et al. 2005), but only a small portion of these emissions might be required to slow the decay of wood components so that they remain an effective carbon sink. In addition to heating and cooling, some house components need to be repaired or replaced periodically, and these activities are more directly attributable to wood carbon storage. The greenhouse gas emissions associated with maintenance of the wooden portions of CORRIM's model houses over a 75-year lifespan were 1,066 and 890 kg CO_2e respectively (Winistorfer et al. 2005)—a ratio to 100-year wood carbon of about 0.06*.

TABLE 3.

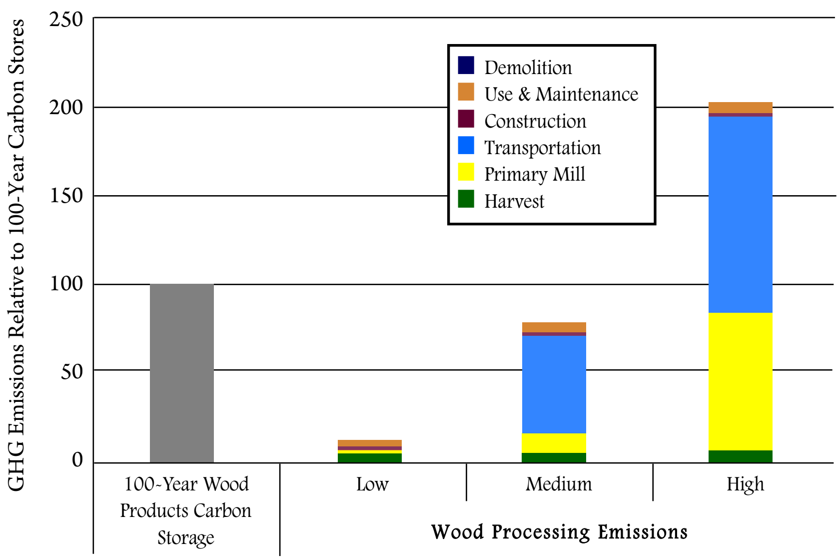
Greenhouse Gas Emissions from Solid Wood Products Processing

	Ratio of non-wood energy GHG emissions to wood storage in year 100 (CO_2e basis)		
Processing Step	*Low*	*Medium*	*High*
1. Harvest and transport to mill	0.04	0.05	0.07
2. Primary processing	0.02	0.10	0.77
3. Secondary processing			
Construction	0.008	0.009	0.011
Transport to end use	0.00	0.56	1.12
4. Use/maintenance	0.06	0.06	0.06
5. Demolition and disposal	0.003	0.003	0.003
Total	**0.13**	**0.78**	**2.03**

Sources: See text.

FIGURE 4.

Energy and Other Process-Related Greenhouse Gas Emissions Associated with Wood Products



Source: Table 3.
Note – excludes secondary processing emissions.

5. Disposal

Again in the CORRIM model homes study, demolition and transport to the landfill of the wood materials in the two houses released another 65* kg CO_2e (Minneapolis) and 49* kg CO_2e (Atlanta) (Winistorfer et al. 2005), for a ratio to 100-year wood carbon of less than 0.01. Additional expenditures of fossil fuel energy would occur at the landfill itself to move and bury wastes, but these were not included.

Thus, as indicated in Table 3 and Figure 4, the entire process of transforming wood into a form suitable for carbon storage causes substantial GHG emissions, and in some cases long-distance transport may cause emissions to exceed the CO_2e storage value.

Broader System Effects

The stump-to-dump analyses outlined above track wood carbon losses and fossil fuel energy use throughout the life cycle of a wood product, but timber harvest also has broader system effects, on forest ecosystems as a whole as well as on markets and the larger economy.

The effect of timber harvest for wood products on the broader forest ecosystem depends on the assumptions of a particular study. At one extreme, some studies assume that without a wood products market, no forests would exist; hence wood products should be credited for all carbon sequestered by the source forest. At the other extreme are studies assuming that without a wood products market, natural forests would remain undisturbed and would continue to fix carbon at a slowing but still significant rate for centuries; hence any harvest activity reduces carbon stores, at least temporarily. The typical situation lies somewhere in the middle.

PHOTO BY JOHN ZAPEL, HOLLY MOUNTAIN RESOURCES, LTD., PROVIDED BY RURAL TECHNOLOGY INSTITUTE

The effect of a particular forest management regime on greenhouse gases depends upon the volume of standing trees maintained over time, as well as on soil and forest floor impacts, including road building.

A key determinant of the broader ecosystem effect of wood products is the particular management system that is applied to the source forest. Multiple studies have compared the carbon storage implications of different forest management systems, accounting for carbon stored in the forest, in wood products in use, and in landfills. Some sources assume that sustained yield guarantees the carbon-neutrality of wood, but sustainability of harvest volumes is actually a poor indicator of overall GHG benefits of the management regime. For example, a management regime that involves periodic light harvests and maintains high forest stand volumes, and a regime using clearcuts with short rotations and low average stand volumes, will both produce "sustainable" harvest flows, but they have very different carbon implications.

The volume of live and dead wood maintained on the site over time is a better indicator than the sustainability of harvest flow to assess the carbon sequestration contributions of a particular forest management system. Management regimes that reduce the standing stock of timber, even if they produce a sustainable flow of timber over time, will have smaller GHG benefits than regimes that maintain high stand volumes (Liski et al. 2001; Hoover and Stout 2007; Ray et al. 2007; Depro et al. 2008;). Even very old stands continue to build carbon reserves, particularly in the soil (Luyssaert et al. 2008). For young secondary managed forests, the carbon balance depends upon multiple factors, including the effect of harvest on stand regeneration, the proportion of wood converted to long-lived versus short-lived products, the rate of decomposition and amount of methane emitted by discarded products and the extent of reuse, and the growth dynamics of the particular forest type. For older forests with a low risk of major disturbances, conversion to young, fast-growing forest will cause large amounts of GHG emissions as the old stand is removed (Harmon et al. 1990), and it may take decades or even centuries for a sustainable harvest regime to work off this initial carbon debt.

In addition to readily observable effects on standing timber and carbon volumes, harvest operations can affect soil and forest floor carbon stores through physical disturbance. Surprisingly little is known about these effects, but in general, logging can be expected to reduce forest floor carbon. Early research by Covington (1981) indicated that forest floor biomass decreased by half during the 15 years following clear-cutting of northern hardwood stands, presumably due to faster decomposition and reduced deposition of litter. Harmon et al. (1990)

Even the best forest growth models cannot predict future conditions, disturbance events, or forest responses with much certainty. Forest climate strategies will need to adapt to a shifting reality.

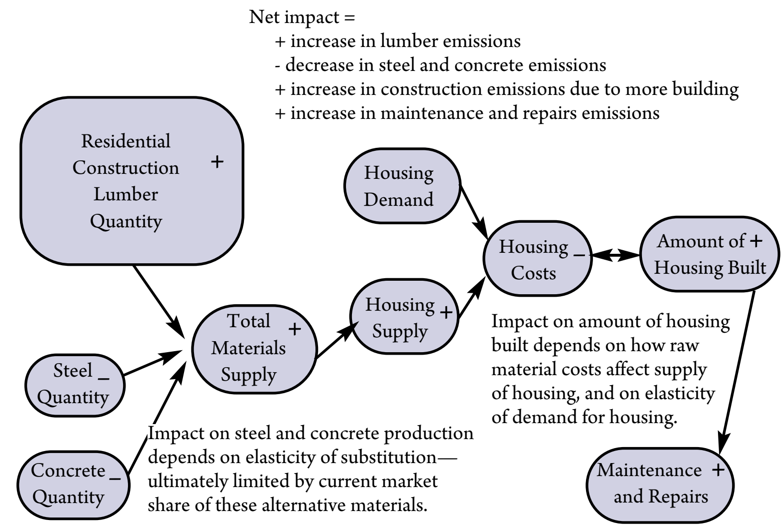
estimated that fine woody debris and forest floor carbon would decrease from 26 to 7 metric tons per hectare if an old-growth Douglas fir stand were converted to a 60-year rotation. Removal of whole trees appears to decrease forest floor carbon as compared to removal of sawlogs only (Johnson et al. 2002). A recent review of studies relating forest management practices to soil carbon stores indicated that thinning generally leads to lower forest floor carbon due to faster decomposition and less litterfall, despite the pulse of carbon from harvest residues (Jandl et al. 2007). Effects on mineral soil are less pronounced, and depend on the degree of disturbance, but clearcutting can lead to overall carbon deficits for up to 20 years as immediate losses of carbon from the soil and forest floor outweigh new growth and litterfall. Yanai et al. (2003) paint a more complex picture, citing studies that show *slower* litter decomposition after clearcuts (due to a less favorable environment for decomposer organisms), combined with possible accelerated losses of carbon within the soil organic horizon, and mixing of some litter into mineral soil by logging disturbance. Forestland managed for timber may also lose soil and forest floor carbon due to clearing for logging roads. And finally, loss of cover in wet boreal forests with deep peat soils could trigger release of the vast amounts of carbon stored in those soils.

Beyond the relatively short-term effects on standing trees and the longer-term effects on the forest floor and soils, timber harvest can also affect the resilience of forests to disturbances over time. In fire-prone forests, thinnings that reduce excess fuel loads may reduce the frequency or severity of fire, protecting forest carbon reservoirs into the future (Oneil et al. 2007). However, thinning in moist forests may make forests more vulnerable to ice damage or wind throw. Timber operations that remove invasive exotic species can produce more diverse stands that better resist stresses from droughts to pest outbreaks; by the same token, disturbance from harvest activities can also help spread invasives that inhibit regeneration of tree species with high carbon storage potential. Single-age, single-species plantations may grow rapidly during intermediate stand ages, but can be more vulnerable to future disturbances and consequent carbon losses. Even the best forest growth models cannot predict future conditions, disturbance events, or forest responses with much certainty. Forest climate strategies will need to adapt to a shifting reality, with the state of scientific knowledge continuously scrambling to keep up as forests and management methods change and develop.

In addition to ecosystem effects, changes in wood products volume may also reduce GHG emissions as markets substitute wood for more GHG-intensive materials. However, the actual degree of substitution is extremely difficult to document. Simply producing more wood products will not do the trick. The ultimate impact of expanded lumber production on GHG emissions depends on a) the elasticity of substitution of wood for alternative materials, b) the impact of materials availability on housing supplies, and c) the elasticity of demand for housing (Figure 5). The first factor, the elasticity of substitution for alternative building materials, is likely to be low, because wood is already the "business as usual" technology for home construction and residential furniture in the U.S. (used for 90% to 94% of one- and two-family homes, Gustavson et al. 2006) and it is difficult to build wooden high-rises (usually framed with steel) or foundations (usually concrete). Considering the other two factors, if abundant lumber drives down housing costs (b),[15] and if people respond by building more or larger houses or renovating existing ones (c), expanding the lumber supply

FIGURE 5.

Greenhouse Gas Emissions Impact of Expanded Lumber Production



could well result in *more* overall GHG emissions as fossil fuels are burned to construct and maintain those homes. Overall, then, it would seem that the possible GHG benefits of substitution are relatively low for long-lived wood products.

Biomass

The discussion above traces the greenhouse gas emissions associated with wood products flows. An analysis of the greenhouse gas emissions associated with wood fuels is closely related, because woody biomass that is burned to generate heat or electricity is often a byproduct of both timber cutting operations and the processing of wood products. Unlike wood products, wood fuels lack any carbon storage benefit, so substitution effects comprise the entire climate benefit of these fuels. Fossil fuels are currently the dominant source of energy, so there is much greater substitution opportunity for biomass than there is for wood in construction. As for wood products, however, the benefits depend upon wood fuels actually reducing fossil fuel use, and not simply on expanded woody biomass use.

As a fuel, wood unquestionably has a smaller atmospheric carbon impact than coal, oil, or natural gas. Yet wood fuels are definitely not, literally speaking, “carbon neutral.” First, an analysis of the GHG benefits of wood fuels must reflect the fact that they, like wood products, require fossil fuel energy to produce and transport. In the case of wood-chip fuel, the fossil fuels used to harvest, chip, and transport wood release about 5% of the CO_2e contained in the fuelwood portion of the tree (Mann and Spath 1997).[16] This figure may underestimate actual transport energy, as it assumes haul distances of only 17 miles and does not account for truck idling time while loading and unloading, which one source estimated could be as high as 60% of total truck run time (Hakkila and Aarniala 2002). Small-scale biomass projects with a localized “woodshed” can minimize the fossil fuels used to transport bulky solid wood fuels.

Wood pellets require more processing than wood chips. One Wisconsin study found that wood pellets used 6% to 9% as much fossil fuel energy in processing as the energy contained the pellets, compared to wood chips at 2% to 3% (Katers and Kaurich 2006).[17] Fossil energy used to transport and process heating oil, by comparison, was 16% to 25% of the energy contained in the

[15] This effect of abundant lumber is likely small, since wood is typically only about 10% of overall building costs.

[16] When comparing fossil fuel consumption associated with various energy sources, it is important to consider how each study treats the energy embedded in equipment as well as upstream and downstream energy use—fossil fuels themselves also require energy for extraction, processing, and transport.

[17] Because wood fuels contain more water (and otherwise burn less efficiently) than heating oil (see below), fossil fuel energy as a percentage of useful heat will be slightly higher than these percentages.

fuel (Katers and Kaurich 2006). Wood fuels clearly have much lower GHG emissions from processing and transport than fossil fuels, but their fossil-based emissions are not zero.

Liquid biofuels require even more energy to produce than solid fuels. Pimentel and Patzek (2005) estimate that harvest, transport, and processing of wood for cellulosic ethanol uses 57% *more* energy from fossil fuels than the energy contained in the ethanol itself. Even if cellulosic ethanol is produced using steam heat generated by wood, this study estimated that its production still requires 73% as much fossil fuel energy as the ethanol itself contains. A study by Argonne National Laboratory for the U.S. Department of Energy (Wu et al. 2006), in contrast, estimates that cellulosic ethanol will use only 16% as much fossil fuel energy as the energy contained in the ethanol and could reduce GHG emissions by 85% compared to burning gasoline.[18]

In addition to fossil fuels used to process wood fuels, combustion and conversion are generally less efficient for wood than for fossil fuels, so more units of heat (BTUs) must be generated to produce a given amount of useful energy. Solid biomass fuels like wood are used primarily for heat (in traditional wood stoves and furnaces that burn cordwood, wood gasification plants that use chips, and stoves or boilers that burn wood pellets) or to generate electricity (over 80 wood-fueled power plants nationwide have a combined output of nearly 1,700 megawatts). The most efficient wood use is for heat alone (about 65% of the potential BTUs in wood burned in a typical home wood stove are converted to useful heat, and up to 75% in gasification systems according to Biomass Energy Resource Center 2009), or for combined-cycle heat and power, also known as co-generation (60% to 80% efficient at converting wood energy to useful energy). Wood-fueled electric utility plants, on the other hand, may be only 18% to 24% efficient (U.S. Forest Service Forest Products Lab 2004). In comparison, modern oil or gas furnaces may be up to 97% efficient, electricity generated from oil or coal is about 30% to 35% efficient, and coal for space heat has about the same conversion efficiency as wood.[19]

When evaluating the potential GHG benefits of substituting wood fuels for fossil fuels, the relative carbon content of alternative fuels must also be considered. Wood has a lower hydrogen content than fossil fuels, which causes it to release more carbon per unit of heat. Wood releases 21% more CO_2 per BTU than fuel oil, and 67% more than natural gas, but 14% less than anthracite coal (U.S. Energy Information Administration 2008a).[20] So replacing oil or natural gas with wood actually increases greenhouse gases released per BTU, even if the boiler burns with equal efficiency. Replacing coal with wood, on the other hand, potentially reduces emissions per BTU if the wood is burned efficiently. In sum, because of efficiency and chemistry differences, wood fuel may generate up to twice the CO_2 per unit of useful heat or electricity as fossil fuels, with the substitution most favorable for coal.

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[18] Differences are due to contrasting assumptions. Wu et al. use much lower values for energy embodied in equipment, assume no fertilization for woody biomass, incorporate the energy content of byproducts, and assume increasing yields over time as technology improves.

[19] Wood stoves and furnaces may be close to oil and gas in efficiency at peak output, but wood equipment is more difficult to start and stop on demand, and hence often runs with incomplete combustion (producing charcoal and ash and increased emissions rather than heat) for part of the season as it operates at lower temperatures and with limited oxygen supply.

Since wood actually releases more greenhouse gases per unit of useful energy than fossil fuels, the climate benefits of a switch to wood depend heavily on the assumption that the source forest continues to take up carbon as rapidly as it is released by burning, and even then there will inevitably be some delay between emissions and reabsorption. Hence, an assessment of the GHG impacts of biomass use on the source forest must also account for the full ecosystem effects of intensified management needed to increase biomass supplies. It is true that burning fossil fuels releases carbon that had been removed from the atmosphere hundreds of millions of years ago, while growing trees and burning their wood cycles carbon in and out of the atmosphere over a scale of a few decades. But timing still matters. If the source forest regenerated instantly, biomass would earn its "carbon-neutral" label, but the longer it takes to regenerate forest carbon after a biomass harvest, the longer that carbon dioxide remains in the atmosphere exerting its heating effect.

Waste wood burned for energy comes closest to true carbon neutrality, as it has already been removed from the forest and would otherwise decompose without energy benefits. New wood fuel plants are often promoted as running on wood waste, but unfortunately there is very little true waste remaining in the wood processing system. Perlack et al. (2005) calculated the amount of additional biomass fuel that could feasibly be used in the United States each year, and estimated that there are only 8 million tons of unused mill waste and 28 million tons of urban and consumer wood waste that could be captured for this purpose. The remainder of the woody biomass documented in the report, a total of 190 million tons, would come from the forest—41 million tons of logging residues, 60 million tons from forest fuels reduction treatments, and 89 million tons from all sources generated as byproducts of potential *increased* harvest and wood products consumption.

Removing 190 million more tons of woody biomass from U.S. forests annually (plus harvesting sufficient additional roundwood to generate enough new logging residue and wood waste) would reduce forest carbon stores in the short term, and could also affect carbon sequestration capacity in the longer term through its effects on site productivity and soil carbon. Increased use of whole-tree harvest technology and collection of widely scattered and bulky residues could create unintended impacts on soils and the forest floor as well as increasing fossil fuel consumption associated with harvest. In special cases, removal of excess woody material can increase forest carbon stores by reducing losses from catastrophic wildfire. But in general, there is a trade-off between burning wood and storing its carbon on the stump. As economists, the "dismal scientists," like to say, "There is no such thing as a free lunch."

Because of fossil fuel energy required to produce wood fuels, differences in combustion efficiency and fuel chemistry, and possible impacts on source forests, woody biomass cannot be considered a truly carbon-neutral energy source. Harvested judiciously, however, with care for long-term forest health, and with an emphasis on small-scale space heating applications, it can help reduce greenhouse gas emissions and help us through the transition to truly renewable energy sources. Incentives and regulations designed to boost use of wood fuels need to minimize the negative effects and promote uses with the greatest net benefit.

Because of fossil fuels required to produce wood fuels, differences in combustion efficiency and fuel chemistry, and possible impacts on source forests, woody biomass cannot be considered a truly carbon-neutral energy source.

[20] These comparisons assume kiln-dried wood with complete energy capture, so typical fuelwood in a typical home stove would burn much less efficiently.

Policy Implications

The analyses above revealed that wood losses along the production chain, release of methane from landfills, and GHG emissions from fossil fuel energy used to produce and transport wood products are significant. As a result, long-lived wood products ultimately store only a small portion of the carbon removed from the forest by logging. Moreover, the most significant of these stores are in landfills, rather than in wood products in use. When process energy emissions are included, the U.S. forest products industry as a whole, including paper, releases nearly twice the greenhouse gases (measured in CO_2e) that it stores in products and landfills, even excluding the effects of harvest on forest carbon (Skog et al. 2008).

Despite these broad patterns, the emissions associated with different wood products streams are extremely variable and complex, making it difficult to recommend any uniform policy to enhance greenhouse gas reduction through increased wood products flow. Only life-cycle analysis of specific products and regions can determine whether a particular wood product stream has GHG benefits. For any region or product mix, however, shifting use toward longer-lived products, reducing wood waste at all stages, recovering used wood for new products or energy, reducing processing and transport energy, and capturing more landfill methane could all lower the carbon footprint of wood products.

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Processing recovered materials into new long-lived products can extend the storage life of wood carbon already removed from the forest. For instance, discarded pallets may be remanufactured into hardwood paneling.

The clearest climate benefits of wood use, for either products or fuel, come from substitution effects—that is, consequent reduced use of alternative fossil-fuel-intensive materials. This is obvious in the case of biomass fuel, but it is true of wood products as well. In the case of wood products, the opportunities for substitution may be limited, but when substitution does occur it reduces fossil fuel emissions "forever." Unfortunately, simply expanding production will not guarantee that substitution actually occurs. Several policy options could tie wood use directly to reduced dependence on fossil fuels: 1) impose full environmental costs on fossil fuel-based and wood-based products alike, hence giving wood a competitive advantage (a carbon tax or cap-and-trade program would do this by increasing the cost of fossil-fuel-intensive alternatives, as long as similar policies applied for trading partners); 2) encourage voluntary choices that favor wood (provided the advantages are thoroughly documented), through approaches like green building standards or renewable energy certificates; 3) offer temporary subsidies or tax breaks to switch fossil-fuel furnaces to clean-burning wood furnaces where sustainable supplies are available; 4) encourage community-scale wood heat projects that use locally sourced wood and are likely to have fewer environmental and fossil energy impacts than larger-scale projects.

Increased demand for wood products resulting from such policies will ultimately reward wood producers through higher prices, with no need to subsidize wood production directly. Climate policies should not directly reward "second-best" strategies (like building with or burning wood) without reliable proof that they replace a "third-best" alternative. The "first-best" strategy remains a reduction in the overall use of resources, and direct subsidies for wood use could lead to excess capacity, excessive energy use, and unintended harm to forest health. Since the climate benefits of wood fuels and wood products alike depend upon maintenance of high carbon stores in source forests over time, any temporary subsidies must be accompanied by rigorous forest sustainability standards.

A clear and accurate picture of the climate effects of wood use is critical to the development of effective greenhouse gas reduction strategies. With tightening international and national commitments to reduce GHG emissions, accounting for forest and harvested wood carbon has received increasing attention. The treatment of these carbon pools in national GHG inventories and under cap-and-trade systems will ultimately influence the success of climate change mitigation efforts. The last section of this report provides a brief overview of how wood products have been treated under climate policy to date. A topic of current interest and controversy is whether and how wood products carbon should be credited as part of offset projects, so we also discuss some key issues that must be resolved if this is to be done effectively—that is, if wood products carbon is to help reduce greenhouse gas emissions.

The Role of Harvested Wood Products in Climate Policy: A Short History

Nations that signed the United Nations Framework Convention on Climate Change (Kyoto Agreement) in 1992 agreed to report emissions and sequestration of greenhouse gases. The guidelines developed for these inventories initially omitted wood products carbon, under the assumption that new wood products would simply replace discarded ones with no net change in this carbon pool (IPCC 1996, Chapter 5, Box 5, p. 5.17). Countries could include harvested wood products in their reporting, however, if they could clearly demonstrate that stocks of products in use and in landfills were increasing over time.

As countries gained experience with GHG reporting and as the start of the first 2008-2012 Kyoto commitment period approached, interest grew in crediting carbon stored in wood products and in landfills as part of national inventories to help balance emissions from other sectors. In 2003, the Intergovernmental Panel on Climate Change (IPCC) issued Good Practice Guidance for Land Use, Land Use Change, and Forestry, which included methodologies for measuring carbon in wood products in use and in landfills (IPCC 2003, Appendix 3.a.1), and the most recent Guidelines for National Greenhouse Gas Inventories (IPCC 2006) now incorporate these recommendations.

Beyond simply measuring greenhouse gases, Kyoto Agreement signatories made commitments to meet emissions reduction targets and it took several follow-up meetings to agree on how to treat the forest sector for these targets. The final rules for the 2008-2012 commitment period require countries to report the GHG impacts of land use changes (deforestation and afforestation), and allow countries to choose whether or not to include emissions from and sequestration by managed forestlands that remain forested (with individual-country limits on use of sequestration by managed forests to balance their industrial emissions).[21] At this time, increased carbon in wood product pools cannot be credited toward emissions reduction commitments, though negotiations are ongoing about the inclusion of forest products carbon in future commitment periods.

In both international and U.S. contexts, cap-and-trade mechanisms are gaining acceptance as an approach to reducing GHG emissions. Theoretically, market-based trading may be used within a nation or between nations to allocate emissions reduction efforts to least-cost options under a defined emissions cap. Through allowance trading, parties with surplus emissions reductions can market them to those with higher compliance costs. Allowance trading systems have gained acceptance through programs like the U.S. EPA's cap-and-trade program for sulfur dioxide.

Initial cap-and-trade proposals treat forests and agriculture as uncapped sectors. One way to encourage emissions reductions or GHG removals by uncapped sectors is to allow them to sell documented GHG reductions—that is, increased sequestration or emissions reductions beyond "business as usual"—as "offsets" to entities in capped sectors. These offsets can serve as a substitute for direct emissions reductions by those entities. When forestry projects are used to offset emissions from regulated sources, questions about what counts as a GHG reduction can become complex. In general, the U.S. has taken a more favorable attitude toward forest offsets than many other countries. The European Union Emission Trading Scheme, for instance, currently excludes forestry offset projects.

U.S. forests currently capture about 10% of national GHG emissions, thanks to regrowth of forests on abandoned agricultural land and intensively cut timberland. Receiving credit for this sink, at the national accounting level or through individual offset projects, would reduce compliance costs for other sectors. Crediting wood products carbon storage would further expand the range of forest-based offsets. Of course, only changes in practice that supplement "business as usual" sequestration in these sinks will actually contribute to GHG reductions. Emerging regulatory schemes in California, the Northeast (Regional Greenhouse Gas Initiative), and the West (Western Climate Initiative) include forest offset options, and each of these arenas is considering inclusion of wood products pools. Crediting wood products carbon storage would further expand the range of forest-based offsets. Emerging regulatory schemes in California, the Northeast (Regional Greenhouse Gas Initiative), and the West (Western Climate Initiative) include forest offset options, and each of these arenas is considering inclusion of wood products pools. The U.S. Department of Energy's voluntary 1605(b) greenhouse gas registry and the Chicago Climate Exchange also credit wood products carbon for projects registered or offsets traded.

[21] Canada, for instance, chose to exclude managed forests from its 2008-2012 Kyoto Agreement-mandated reporting, as scientists estimated that there would be a high chance of managed forests acting as a source rather than a sink during this period, due to increasing fire and insect outbreaks.

Accounting for Wood Products in Forest Offsets

Harvesting timber as part of an offset project introduces a complex series of greenhouse gas impacts that spread back to the source forest and outward through the economy. Though many of the issues can be addressed by the life-cycle assessment approach outlined in the first sections of this report, the offsets context introduces new questions about what impacts should be credited or debited to the offset project provider. Incomplete accounting could fail to properly reward significant emissions reductions, whereas crediting activities of questionable climate benefit could inadvertently encourage GHG-emitting activities.

Because the U.S. is somewhat unique in its emphasis on offsets from forest carbon sinks, particularly in proposing to credit wood product pools, it is critical to get the accounting right in order to maintain credibility as our nation begins to play a role in global GHG reduction efforts. A good project accounting system will: 1) define a system boundary that captures major effects; 2) include significant GHG pools and fluxes; 3) set additionality criteria that ensure that "business as usual" activities are not credited (including defining accurate baselines); 4) account for significant leakage (emissions outside the project boundary that are affected by the project); 5) ensure that carbon is stored "permanently;" and 6) address uncertainties and risks by discounting credits and/or pooling risk across multiple projects. The discussion below indicates how each of these criteria applies to wood product pools as part of forest offsets.

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1. Project Boundary

One boundary question arises for wood products projects operating in isolation from source forests. It is forests that actually remove carbon from the atmosphere, and production of wood products merely slows the rate of release back into the atmosphere when some of that carbon is removed from the forest site. Because sequestration on the source forest and in harvested wood are so intertwined, stand-alone wood products offset projects would exclude many significant project impacts. Wood products should only be considered as a possible carbon pool within the context of forest management projects, and then only if full accounting of GHG impacts is required.

The second critical boundary question is the treatment of emissions beyond the geographic boundary of the forested property. The following principles for project accounting from the IPCC Good Practice Guidance for Land Use, Land Use Change, and Forestry (2003) provide guidance for defining system boundaries in offset projects:

> In a general sense, project boundaries can be thought of in terms of geographical area, temporal limits (project duration), and in terms of the project activities and practices responsible for greenhouse gas emissions and removals that are significant and reasonably attributable to the project activities (Section 4.3.2, p. 4.90).
>
> Project operators need to determine and report the greenhouse gas emissions from direct fossil fuel and electricity use in mobile and stationary equipment (Section 4.3.3.7, p. 4.109).

Long-distance shipping is an important source of fossil fuel emissions that should be reflected in harvested wood carbon offset accounting. Exports of logs and lumber to China have grown in recent years, and emissions from this source would fall outside of Kyoto commitments (Zhang Jiagang, China, 2001).

Emissions associated with processing, transport, use, and disposal of wood products are certainly "reasonably attributable" to the wood carbon storage function, as without these steps a tree removed from the forest would decompose much more rapidly. However, projects that claim offset credits for wood stored off-site depend on capped sector entities to perform these services. It is not at all clear how to handle this anomaly since capped sectors themselves are not eligible to sell offsets.

In an offsets context, accounting for energy emissions matters because forest project developers will choose between strategies that accumulate more carbon in the forest ecosystem and strategies that remove more carbon for storage in products and landfills. Projects that include timber harvest will have a competitive advantage because timber revenues help cover project costs. Crediting these projects for the full amount of carbon stored in wood products, without accounting for associated emissions, would skew the offsets mix toward timber harvest projects, and would increase pressure on limited fossil fuels and raise costs elsewhere in the economy. Considering only the sequestration aspect would be like a cost/benefit analysis that considers only benefits. Some wood products clearly result in more processing emissions than the carbon they store, and these activities should not be subsidized by valuing the carbon stored in final products and landfills without accounting for GHG emissions along the production path.

Some claim that under an economy-wide program offset projects should not be responsible for fossil fuel-related emissions outside the forest, since those emissions are already capped. By this line of argument, allowance costs associated with processing and transport will affect offset providers through a lower value for raw harvested wood. But allowance costs will also raise prices for finished wood products and lower profits for wood businesses, among other effects, so raw wood values will not reflect the entire cost. Lower timber prices will also apply equally to all forest landowners, not just offset providers. Hence the burden is on regulators to ensure equal treatment for forest offset strategies through project accounting that reflects net carbon storage, rather than gross storage. A requirement that offset projects maintain pre-project forest carbon stores throughout the project period would also help guard against unintended intensification of harvest.

2. Carbon Pools

Most carbon accounting protocols call for periodic sampling of all significant carbon pools, with offset providers credited or debited based on stock changes.

This system would adequately reflect forest carbon reductions directly caused by timber harvest, as well as losses occurring from natural processes in the absence of harvest activity. The volume of standing live and dead trees would decrease after harvest; forest floor and down dead wood pools would briefly increase and then decrease as material rots over several years. Carbon losses from the stumps and roots of harvested trees would also be accounted for if below-ground carbon is estimated from above-ground tree biomass, as a missing tree would lower the post-harvest below-ground estimate. Long-term losses of soil and litter carbon due to harvest disturbance are less likely to be captured through periodic inventories due to the difficulty of sampling soils adequately. Because soils commonly hold one-third to one-half of forest carbon, a small percentage change in soil carbon can significantly affect total forest carbon. When soil-carbon impacts are underestimated, this can make short-rotation, intensive-production forestry look more favorable from a carbon perspective than it really is.

Measurement of wood product carbon stocks and flows is a bit trickier. Documentation of carbon storage in wood products for offset projects would probably concentrate on the portion converted to solid lumber, plywood, or panels, and perhaps the portion remaining intact in landfills. Because of the complexities of tracking these pools over time, the U.S. Department of Energy introduced the 100-year method into its voluntary 1605(b) program. This approach allows project developers to report carbon stocks expected to remain in wood products and landfills 100 years after harvest. Projects relinquish claims to shorter-term carbon stores, in exchange for receiving permanent credit for stores present in year 100. Registry participants are provided with a set of tables developed by the USDA Forest Service (based on Smith et al. 2006), which are sufficiently accurate for a voluntary registry.

In an offset context, however, this simple approach is inadequate. Regional data in the 1605(b) tables blend results from very diverse operations—with different management styles and land use histories; harvesting logs of various species, sizes, and qualities; and shipping to mills with different product mixes and equipment—all of which creates extremely variable patterns of carbon storage over time. Without direct sampling of a particular wood products stream, adequate discounting of offset credits to reflect the substantial uncertainty of model estimates would likely eliminate creditable wood products carbon altogether. Tracking the wood processing path of an individual project would encourage efficiency, recycling, and channeling of wood to long-lived products to improve retention of wood carbon over time. Some 1605(b) parameters, such as the carbon density of various finished products, apply across all projects and can be combined with project-specific data to develop estimates of carbon stored in wood products. Changes in wood product technology and consumer behavior also demand periodic adjustments in estimation parameters.

3. Additionality

After establishing appropriate project boundaries and defining carbon pools, an offset project claiming wood product credits would compare the flow of wood products under planned project management to the flow under a "business as usual" scenario. The *difference* in GHG emissions would comprise the wood products component of project carbon credits. Developers of offset standards are just beginning to consider how to define a wood products baseline, against which an offset must measure its carbon storing activities. Should the baseline be the historical flow from this property, the projected future flow, or the average from similar properties? Additionality questions are an important but unresolved issue that all offset protocol developers are still wrestling with.

4. Leakage

Additionality is further complicated by market leakage and substitution effects, both outside the direct control of the offset developer. At its most extreme, leakage seems to confound any attempt to change "business as usual" practices, as project actions may be undone by non-project *re*actions. If a project lowers historic levels of timber harvest in order to accumulate forest carbon, but nearby properties respond with increased cutting that depletes their carbon stocks, leakage adjustments would reduce creditable project carbon. If a project increases harvest to store more carbon in wood products, and nearby properties respond with reduced cutting, this would likewise undercut wood carbon gains. Work to estimate and compensate for leakage in forest offset projects is ongoing (see Willey and Chameides 2007 for one suggested method).

Substitution is really a type of leakage with effects extending to substitute products. For the harvest-reducing project example, inclusion of substitution effects might penalize the project if the harvest reduction indirectly causes increased use of concrete, steel, or plastics. Conversely, a project that increases timber harvest might claim greenhouse gas reductions from reduced use of concrete or steel framing. As explained in the Broader System Effects section above, data are lacking to actually demonstrate substitution effects in the economy, and crediting such an uncertain outcome would be out of place in an offset project.

An analogy might help provide context for interpreting substitution claims. The owner of a hybrid vehicle might claim that every mile driven in that vehicle reduces GHG emissions, and is worthy of a climate subsidy, because the owner *could* have chosen to drive a conventional sport utility vehicle instead. For the individual driver faced with a choice of vehicles, the hybrid is undoubtedly a more climate-friendly choice, just as for a builder use of wood might be more climate-friendly than concrete. Yet a superior GHG-reducing strategy would be to stop driving altogether or to reduce building size, extend building life, and reuse waste wood. If this driver never owned a sport utility vehicle nor had plans to purchase one, or if the hybrid was driven more miles due to lower driving costs, then the benefits would be entirely fictional. Moreover, if hybrid vehicles or wood construction are already the "business as usual" technologies, no credit may be claimed for their use. Even where they are not dominant, actual substitution must still be demonstrated.

Because these indirect market effects are beyond the control of an offset provider and are mind-bendingly complex, some protocols exclude them from project carbon accounting. Climate policies that directly support efficiency, conservation, and GHG-reducing technologies (e.g., by subsidizing research or setting appliance standards) are better suited than offset projects to address these economy-wide factors.

5. Permanence

Wood products do not store carbon permanently, though landfills apparently can store it for decades or even centuries (our experience with landfills is too short to know this for certain). Since offsets enable continued GHG emissions above the cap set by public policy, and since those emissions permanently shift carbon from the lithosphere to the biosphere, it is important to use conservative assumptions about the longevity of carbon storage through terrestrial offset projects, particularly for wood products and landfills that do not sequester additional carbon over time as forests do. IPCC's Good Practice Guidance for Land Use, Land Use Change, and Forestry (2003) uses very conservative default half-lives in use of 30 years for all solid wood products and 2 years for paper. Use lives change over time as new technologies extend product life or introduce more disposable products or as consumer habits change, so parameters would need to be updated frequently.

Since it would be impossible to track wood flows from an offset project to particular landfills, regional or national average decomposition rates would be the only option for tracking the fate of landfilled wood carbon. Ongoing monitoring will be critical to improve data on landfill releases, and to update GHG emissions estimates as waste management practices change over time. If the longevity of products and waste are tracked as part of wood pools in offset projects, practices that increase product life or boost waste recovery would be rewarded.

6. Uncertainty and Risk

The wood products life-cycle summary in the first section of this report illustrated the variability of wood processing pathways in terms of their carbon losses and energy requirements. Due to diverse sources and processing methods, it is impossible to develop a single reliable error estimate for wood products carbon measurements. In the face of substantial uncertainty, wood carbon estimates should use conservative estimation methods and should be discounted for uncertainty if credited to an offset project.

Conclusions

The limited role of forests and wood products in sequestering and storing carbon can be understood through information about basic biology and technology, but choices about how forests and wood products and wastes are treated under climate policy are ultimately a matter of public values. Forest and agricultural operations will likely be excluded from a regulatory cap on greenhouse gases, because their land base often sequesters more carbon than it releases and because their carbon flows are so difficult to measure. Nonetheless, management practices of these operations can reduce as well as increase carbon stores, and the distinction between these entities and regulated ones is a matter of degree rather than kind. The ability to market offsets, should it be incorporated in U.S. cap-and-trade legislation, must be understood as a public policy choice and not a right. Offset standards should be designed to support broad public policy outcomes.

Setting public goals for forests will require weighing the advantages of accumulating more carbon in forests versus the advantages of accumulating it in furniture, homes, and landfills or burning to generate energy. In most cases, boosting forest carbon stores will create stable, self-sustaining carbon reserves at no fossil-fuel emissions cost. Protecting and enhancing forest carbon reserves can also help maintain undisturbed, late-successional forests that are currently rare across the landscape. These forests could provide a refuge for species stressed by a changing climate and provide valuable lessons about how natural systems adapt to new conditions. In contrast, carbon storage in wood products and landfills depends upon continuing fossil fuel use and requires space for housing and landfills that displace carbon-fixing vegetation. At the same time, however, wood products and fuels generate revenue for landowners (an incentive to keep forests as forests), provide material comforts for consumers, and may indirectly reduce GHG emissions by substituting for more fossil-fuel-intensive alternatives.

Wood products and wood fuels have a role to play in a carbon-friendly future. An emphasis on increased wood production, however, can distract from the ultimate goal of reducing use of energy and materials. The U.S. economy currently uses over 2.3 times more energy and 1.5 times more materials per capita than Europe (Rogich et al. 2008; U.S. Energy Information Administration 2008b), yet quality of life indicators are lower in the U.S. than in many European countries. There is clearly room for reducing consumption without harming basic human welfare, and the best climate change strategies will keep that goal clearly in sight.

Literature Cited

Adams, D.M., R.W. Haynes, and A.J. Daigneault. 2006. *Estimated Timber Harvest by U.S. Region and Ownership, 1950-2002.* Gen. Tech. Rep. PNW-GTR-659. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Barlaz, M.A. 1997. *Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills.* EPA 600/R-97-071. Research Triangle Park, NC: National Risk Management Research Laboratory.

Bergman, R.D., and S.A. Bowe. 2008. Environmental impact of producing hardwood lumber using life-cycle inventory. *Wood and Fiber Science* 40(3):448-458.

Biomass Energy Resource Center. 2009. Personal communication.

BFM, Ltd. 2003. *Wood Waste Recycling in Furniture Manufacturing—A Good Practice Guide.* Banbury, Oxon, UK: Waste and Resources Action Programme.

Borjesson, P., and L. Gustavson. 2000. Greenhouse gas balances in building construction: Wood versus concrete from life-cycle and forest land-use perspectives. *Energy Policy* 28:575-588.

Cornell University Cooperative Extension. 1996. *Material Wastes in New Residential Construction.* Available at http://hosts.cce.cornell.edu/housing/material%20waste%20in%20new%20construction.php (accessed 6/11/2008).

Covington, W. 1981. Changes in forest floor organic matter and nutrient content following clearcutting in northern hardwoods. *Ecology* 62(1):41-48.

Crumpler, P. 1996. *Industrial Wood Waste.* The Source. Georgia Department of Natural Resources, Pollution Prevention Assistance Division. Available at http://www.p2ad.org/documents/tips/industww.html (accessed 5/3/2008).

Depro, B.M., B.C. Murray, R.J. Alig, and A. Shanks. 2008. Public land, timber harvests, and climate mitigation: Quantifying carbon sequestration potential on U.S. public timberlands. *Forest Ecology and Management* 255:1122-1134.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland. 2007. Changes in atmospheric constituents and in radiative forcing. Pages 129-234 in: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, and New York, NY, USA: Cambridge University Press.

Gower, S. 2003. Patterns and mechanisms of the forest carbon cycle. *Annual Review of Environmental Resources* 28:169–204. Available at http://arjournals.annualreviews.org (accessed 10/28/2007).

Gower, S.T., A. McKeon-Ruedifer, A. Reitter, M. Bradley, D.J. Refkin, T. Tollefson, F.J. Souba, A. Taup, L. Embury-Williams, S. Schiavone, J. Weinbauer, A.C. Janetos, and R. Jarvis. 2006. *Following the Paper Trail: The Impact of Magazine and Dimensional Lumber Production on Greenhouse Gas Emissions: A Case Study.* Washington, D.C.: The H. John Heinz III Center for Science, Economics and the Environment.

Gustavson, L., R. Madlenere, H.F. Hoen, G. Jungmeier, T. Karjalainen, S. Klohn, K. Mahapatra, J. Pohjola, B. Solberge, and H. Spelter. 2006. The role of wood material for greenhouse gas mitigation. *Mitigation and Adaptation Strategies for Global Change* 11:1097-1127.

Hakkila, P., and M. Aarniala. 2002. Wood Energy Technology Program newsletter. Finland: TEKES.

Harmon, M.E., W.K. Ferrell, and J.F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247:699-702.

Hoover, C., and S. Stout. 2007. The carbon consequences of thinning techniques: Stand structure makes a difference. *Journal of Forestry* 105(5):266-270.

Houston Advanced Research Center. 2005. *Residential C&D Waste Study.* Houston-Galveston Area Council and Texas Commission on Environmental Quality. Available at http://www.recyclecddebris.com/rCDd/Resources/WasteStudy/ (accessed 6/10/2008).

Intergovernmental Panel on Climate Change (IPCC). 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Volume 3).* Available at http://www.ipcc-nggip.iges.or.jp/public/gl/invs6.html (accessed 9/8/2008).

Intergovernmental Panel on Climate Change (IPCC). 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Japan: Institute for Global Environmental Strategies (IGES) for the IPCC. Available at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html (accessed 9/8/2008).

Intergovernmental Panel on Climate Change (IPCC). 2006. *IPCC Guidelines for National Greenhouse Gas Inventories.* Japan: Institute for Global Environmental Strategies (IGES) for the IPCC. Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (accessed 9/8/2008).

James, C., B. Krumland, and P.J. Eckert. 2007. *Carbon Sequestration in Californian Forests: Two Case Studies in Managed Watersheds.* Sierra Pacific Industries.

Jandl, R., M. Lindner, L. Vesterdal, B. Bauwens, R. Baritz, F. Hagedorn, D.W. Johnson, K. Minkkenen, and K.A. Byrne. 2007 How strongly can forest management influence soil carbon sequestration? *Geoderma* 137:253–268.

Johnson, D.W., J.D. Knoepp, W.T. Swank, J. Shan, L.A. Morris, D.H. Van Lear, and P.R. Kapeluck. 2002. Effects of forest management on soil carbon: Results of some long-term resampling studies. *Environmental Pollution* 116:S201-S208.

Johnson, L., B. Lippke, J.D. Marshall, and J. Comnick. 2005. Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States. *Wood and Fiber Science* 37:30-46.

Katers, J.F., and J. Kaurich. 2006. *Heating Fuel Life Cycle Assessment.* University of Wisconsin Green Bay. Available at http://www.pelletheat.org/3/2007SummerConf/Final%20PFI%20study.pdf (accessed 7/3/2008).

Kline, D. 2005. Gate-to-gate life-cycle inventory of oriented strandboard production. *Wood and Fiber Science* 37:74-84.

Li, Z., W.A. Kurz, M.J. Apps, and S.J. Beukema. 2003. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: Recent improvement and implications for the estimation of NPP and NEP. *Canadian Journal of Forest Research* 33:126-136.

Liski, J., A. Pussinen, K. Pingoud, R. Makipaa, and T. Karjalainen. 2001. Which rotation length is favourable to carbon sequestration? *Canadian Journal of Forest Resources* 31:2004-2013.

Luyssaert, S., E.D. Schulze, A. Borner, A. Knohl, D. Hessenmoller, B.E. Law, P. Ciais, and J. Grace. 2008. Old-growth forests as global carbon sinks. *Nature* 455:213-215.

Mann, M.K. and P.L. Spath. 1997. *Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System.* Golden, CO: Midwest Research Institute for National Renewable Energy Laboratory.

McKeever, D.B. 2002. *Domestic Market Activity in Solid Wood Products in the United States, 1950-1998.* Gen. Tech. Rep. PNW-GTR-524. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

McKeever, D.B. and R.H. Falk. 2004. Woody residues and solid waste wood available for recovery in the United States, 2002. Pages 311-316 in: Gallis, C. (ed.). *Management of Recovered Wood—Recycling Bioenergy and Other Options. Thessaloniki, 22-24 April 2004.*

Meil, J., B. Lippke, J. Perez-Garcia, J. Bowyer, and J. Wilson. 2004. *Phase I Final Report, Module J Environmental Impacts of a Single Family Building Shell—From Harvest to Construction.* Consortium for Research on Renewable Industrial Materials. Seattle, WA: University of Washington. Available at http://www.corrim.org/reports/2006/final_phase_1/index.htm (accessed 2/22/2007).

Milota, M.R., C.D. West, and I.D. Hartley. 2005. Gate-to-gate life-cycle inventory of softwood lumber production. *Wood and Fiber Science* 37:47-57.

Miner, R. 2006. The 100-year method for forecasting carbon sequestration in forest products in use. *Mitigation and Adaptation Strategies for Global Change.* Published on-line at http://www.springerlink.com/content/2l672741l7366751/ (accessed 11/17/2007).

National Association of Home Builders Research Center. 1995. *Residential Construction Waste Management: Demonstration and Evaluation.* Prepared for U.S. Environmental Protection Agency Office of Solid Waste, Washington, D.C., by NAHB Research Center, Upper Marlboro, MD. Available at www.toolbase.org/PDF/CaseStudies/resi_constr_waste_manage_demo_eval.pdf and summarized at http://www.smartgrowth.org/library/resident_const_waste.html (accessed 5/3/2008).

Oneil, E., B. Lippke, and L. Mason. 2007. *Eastside Climate Change, Forest Health, Fire and Carbon Accounting.* Discussion Paper 8 in The Future of Washington's Forests and Forestry Industries, University of Washington Rural Technology Initiative for Washington State Department of Natural Resources. Available at http://www.ruraltech.org/projects/fwaf (accessed 9/11/2008).

Perez-Garcia, J., B. Lippke, D. Briggs, J.B. Wilson, J. Bowyer, and J. Meil. 2005. The environmental performance of renewable building materials in the context of residential construction. *Wood and Fiber Science* 37:3-17.

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. *Biomass as Feedstock for a Biomass and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply.* Oak Ridge, TN: Oak Ridge National Laboratory.

Pimentel, D., and T.W. Patzek. 2005. Ethanol production using corn, switchgrass, and wood; Biodiesel production using soybean and sunflower. *Natural Resources Research* 14(1):65-76.

Pingoud, K., and F. Wagner. 2006. Methane emissions from landfills and carbon dynamics of harvested wood products: The first-order decay revisited. *Mitigation and Adaptation Strategies for Global Change* 11:961-978.

Ray, D., R. Seymour, and N. Scott. 2007. *Simulating the Long-Term Carbon Consequences of Common Timber Harvesting Practices in Maine.* Orono, ME: University of Maine.

Rogich, D., A. Cassara, I. Wernick, and M. Miranda. 2008. *Material Flows in the United States: A Physical Accounting of the U.S. Industrial Economy.* Washington, D.C.: World Resources Institute.

Skog, K., L. Heath, J. Smith, R. Miner, B. Upton, J. Unwin, and V. Maltby. 2008. *The Greenhouse Gas and Carbon Profile of the U.S. Forest Products Sector.* Special Report No. 08-05. National Council on Air and Stream Improvement and USDA Forest Service.

Skog, K.E. 2008. Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal* 58(6):56-72.

Smith, J.E., L.S. Heath, K.E. Skog, and R.A. Birdsey. 2006. *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States.* Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

U.S. Energy Information Administration. 2008a. *Voluntary Reporting of Greenhouse Gases Program, Fuel and Energy Source Codes and Emission Coefficients.* Available at http://www.eia.doe.gov/oiaf/1605/coefficients.html (accessed 10/1/2008).

U.S. Energy Information Administration. 2008b. *World Per Capita Total Primary Energy Consumption, 1980-2005.* Available at http://www.eia.doe.gov/pub/international/iealf/tablee1c.xls (accessed 7/5/08).

U.S. Environmental Protection Agency (EPA). 2006. *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks. 3rd Edition.* EPA530-R-02-006. Available at http://epa.gov/climatechange/wycd/waste/SWMGHGreport.html (accessed 7/11/2008).

U.S. Forest Service Forest Products Lab. 2004. *Wood Biomass for Energy.* Madison, WI: TechLine. Available at http://www.fpl.fs.fed.us/documnts/techline/wood-biomass-for-energy.pdf (accessed 7/3/2008).

U.S. Forest Service. 2007. *Timber Product Output*. Available at http://ncrs2.fs.fed.us/4801/fiadb/rpa_tpo/wc_rpa_tpo.ASP (accessed 6/10/2-08).

U.S. Forest Service. 2008. *Forest Resources of the United States, 2007.* WO-xxx. Washington, D.C.: U.S. Department of Agriculture, Forest Service. Final tables in spreadsheet format, available at http://fia.fs.fed.us/program-features/rpa/ (accessed 9/24/2008).

Willey, Z., and B. Chameides (eds.). 2007. *Harnessing Farms and Forests in the Low-Carbon Economy.* Nicholas Institute for Environmental Policy Solutions. Durham, NC: Duke University Press.

Wilson, J.B., and E.T. Sakimoto. 2005. Gate-to-gate life-cycle inventory of softwood plywood production. *Wood and Fiber Science* 37:58-73.

Wilson, A., and J. Boehland. 2005. Small is beautiful: U.S. house size, resource use, and the environment. *Journal of Industrial Ecology* 9(1/2):277-287.

Winistorfer, P., Z. Chen, B. Lippke, and N. Stevens. 2005. Energy consumption and greenhouse gas emissions related to the use, maintenance, and disposal of a residential structure. *Wood and Fiber Science* 37:128-139.

Wood Waste and Furniture Emissions Task Force. 1998. *Estimating Emissions From Generation and Combustion of "Waste" Wood.* North Carolina Department of Environment and Natural Resources, Division of Air Quality.

Wu, M., M. Wang, and H. Huo. 2006. *Fuel-Cycle Assessment of Selected Bioethanol Production Pathways in the United States.* ANL/ESD/06-7. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, for U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

Ximenes, F.A., W.D. Gardner, and A.L. Cowie. 2008. The decomposition of wood products in landfills in Sydney, Australia. *Waste Management* 28:2344-2354.

Yanai, R.D., W.S. Currie, and C.L. Goodale. 2003. Soil carbon dynamics after forest harvest: An ecosystem paradigm reconsidered. *Ecosystems* 6(3):197-212.

Zhang, D., D. Hui, Y. Luo, and G. Zhou. 2008. Rates of litter decomposition in terrestrial ecosystems: Global patterns and controlling factors. *Journal of Plant Ecology* 1(2):85-93.

Data Appendix – Conversions and Calculations

Item	Original Data and Source	Assumptions	Computed Estimate
Wood Losses			
Rate of decomposition of forest floor litter	Zhang et al. (2008). Decomposition rate (k value) for first-order decay = 0.3.	k = ln(2) / HL, where HL = half-life.	Convert rate of decomposition by first-order decay to half-lives. 0.3 = In (2) / HL; HL = 2.3.
Above-ground logging waste including logging residue plus stumps and small limbs	Logging residue and roundwood volume nationwide (30%) and by region: South Central (28%), Rocky Mountain (22%), North Central (40%), Pacific Northwest (28%), Northeast (47%) (U.S. Forest Service 2008, Table 40). Logging residue and roundwood volume at state level: NV (3%), NH (84%) (Timber Product Output data online at http://ncrs2.fs.fed.us/4801/fiadb/rpa_tpo/wc_rpa_tpo.ASP). Stumps and branches add 14% to softwood logging residue and 24% to hardwood logging residue (McKeever and Falk 2004).	Stumps and branches add ~19% to logging residue on average (mean value between 14% for softwoods and 24% for hardwoods).	Above-ground logging waste as % of roundwood is 19% more than logging residue. National = 0.3 * 1.19 = 36%. Nevada 0.03 * 1.19 = 4%. New Hampshire = 0.84 * 1.19 = 100%. South Central 0.28 * 1.19 = 33%. Rocky Mountain 0.22 * 1.19 = 26%. North Central 0.40 * 1.19 = 48%. Pacific Northwest 0.28 * 1.19 = 33%. Northeast 0.47 * 1.19 = 56%.
Total logging waste including logging residue plus stumps and small limbs and roots	Large roots are 5% to 51%, mean 19%, of total tree biomass in cold temperate and boreal forests (Li et al. 2003).	Apply mean root value of 19% of total tree biomass across United States (omits small roots). Assume all tree parts have same density so that biomass proportions and volume proportions are similar.	If roots are 19% of total tree volume, then 81% of total tree volume is above-ground. A tree with total tree volume = 1 would have above-ground volume of 0.81. If roundwood volume = x and above-ground logging waste including stumps and branches is 0.36x (national), then x + 0.36x = 0.81 and x = 0.81 / 1.36 = 60%. Total tree losses including above-ground logging residue and large roots = 1 - 0.60 = 0.40, or 40% of total tree volume. Computations for states and regions use same stumps/branches/roots percentages but substitute logging residue percentages by state or region. Total logging losses including above-ground logging residue and large roots are 22% for NV, 59% for NH, 39% for South Central, 36% for Rocky Mountain, 45% for North Central, 39% for Pacific Northwest.
Fuelwood as percent of standing tree volume	Fuel as percent of roundwood nationwide (9%) and by region: South Central (3%), Rocky Mountain (51%) (U.S. Forest Service 2008, Table 39).	Multiply fuelwood as percent of roundwood times roundwood as percent of standing tree volume to estimate fuelwood as percent of total standing tree volume.	See above for calculation of roundwood as percent of standing tree volume. Fuelwood as percent of standing tree volume: Nationally, 0.09 * 0.60 = 5%. For South Central, 0.03 * 0.61= 2%. For Rocky Mountains, 0.51 * 0.64 = 33%.
Pulpwood as percent of standing tree volume	Pulp as percent of roundwood for hardwood sawlogs in the North Central region (6%) and softwood pulp in the Pacific Northwest Westside (50%) (Smith et al. 2006, GTR-NE-343, Table D6). 2002 roundwood volumes from Adams et al. (2006, PNW-GTR-659, Table 13).	This source is used because it includes pulp sourced from sawlogs. Multiply pulpwood as percent of roundwood times roundwood as percent of standing tree volume to estimate pulpwood as percent of total standing tree volume.	Estimate national pulp as percent of roundwood (31%) from weighted average based on regional pulp percent of roundwood for hardwood/softwood and sawlog/pulp, weighted by 2002 roundwood volumes from Adams et al. (2006). See above for calculation of roundwood as percent of standing tree volume. Pulpwood as percent of standing tree volume: Nationally, 0.31 * 0.60 = 19%. North Central, 0.06 * 0.55 = 3%. Pacific Northwest, 0.50 * 0.61 = 30%.

Data Appendix – Conversions and Calculations (continued)

Item	Original Data and Source	Assumptions	Computed Estimate
Bark as percent of standing tree volume	15% to 18% of roundwood volume (Smith et al. 2006, Table 5).	Portion of roundwood volume remaining after fuelwood and pulp sorted out = 1 - 0.40 - 0.05 - 0.19 = 0.36. Assume that bark is included in primary processing losses as calculated below, so not deducted separately.	Portion of roundwood volume available for long-lived products that is bark is 0.36 * 0.165 = 6%.
Primary processing losses	General primary processing conversion efficiencies: http://www.borealforest.org/world/innova/processing.htm for circular vs. bandsaw conversion efficiency; Structural Board Association http://osbguide.tecotested.com/faqs/faq_singlepage.html for OSB efficiency.		
Primary processing losses	Log and product masses: PNW lumber: log 1,538 kg, lumber 774 kg (Milota et al. 2005, Table 5); South lumber: log 2,093 kg, lumber 883 kg (Milota et al 2005, Table 5); PNW softwood plywood: log 504 kg, plywood 241 kg (Wilson and Sakimoto 2005, Table 13); South softwood plywood: log 625 kg, plywood 290 kg (Wilson and Sakimoto, 2005, Table 13); South oriented strandboard: log 772 kg, OSB 574 kg (Kline 2005, Tables 1 & 2).		PNW lumber: (1,538 - 774) / 1538 = 50%. South lumber: (2,093 - 883) / 2093 = 58%. PNW plywood: (504 - 241) / 241 = 52%. South plywood: (625 - 290) / 625 = 54%. South OSB: (772 - 574) / 772 = 26%. Primary mill losses range from 26% (OSB) to 58% (South lumber) of log mass.
Primary processing losses	Percentage losses from various studies: 10% (theoretical OSB) to 62% (plywood in Finland).	To get percent of standing tree, multiply mill losses by percent of standing tree volume remaining after logging losses, fuelwood and pulp are removed (36%).	Convert to percent of standing tree by multiplying by 0.36. Range from 0.10 * 0.36 = 4% to 0.62 * 0.36 = 22%. Average loss = 13%, so remaining portion of standing tree in primary products is 36% - 13% = 23%.
Secondary processing losses	Secondary processing losses as percent of lumber or panel volume (Crumpler 1996; Wood Waste and Furniture Emissions Task Force 1998; BFM, Ltd. 2003).	Multiply mill losses by percent of standing tree remaining after primary processing (23%—see above).	Secondary losses range from 27% to 80% of lumber/panels. Secondary processing losses as percent of standing tree volume: 0.27 * 0.23 = 6% and 0.80 * 0.23 = 18%.
Construction losses	Construction losses as percent of lumber or panel volume, (National Association of Home Builders Research Center 1995; Cornell University Cooperative Extension 1996; Houston Advanced Research Center 2005; NAHB, cited in Wilson and Boehland 2005; James et al. 2007; McKeever and Falk 2004;). Conversion factors for lumber and panels: 33 lbs./cubic foot for softwood lumber and 40 lbs./cubic foot (1.25 lbs./square foot 3/8 inch thick) for sheathing (Smith et al. 2006, GTR NE-343, Table D1).	Calculate weight of wood in standard home from volumes using conversion factors. Then apply construction losses to percent of standing tree remaining after primary processing (23%—see above).	Construction losses range from 4% to 21% of lumber/panels. Construction losses as percent of standing tree volume: 0.04 * 0.23 = 1% and 0.21 * 0.23 = 5%.

Data Appendix – Conversions and Calculations (continued)

Item	Original Data and Source	Assumptions	Computed Estimate
Secondary and construction losses combined	Percentages in long-lived uses by primary product; total volume of each primary product produced in United States (Smith et al. 2006, GTR-NE-343, Table D2; and McKeever 2002, PNW-GTR-524, Tables 18, 20, 22).	Secondary processing losses 6% to 18% and construction losses 1% to 5% (see above). Use average losses for construction (3%) and secondary processing (12%). Assume primary products represented in GTR-343 and GTR-524 tables are representative of all primary solid wood products for U.S.	Multiply percent of softwood lumber used in construction and for furniture (Smith et al. 2006, Table D2) times volume of softwood lumber produced in 1998 (McKeever 2002, Table 18) to estimate total volume of softwood lumber used for construction and for furniture. Repeat for hardwood lumber, softwood plywood, OSB, and nonstructural panels. Sum estimated amounts of all primary products used for construction. Repeat for furniture. Estimated proportions as weighted average for all primary products in long-lived uses are 76% used in construction and 24% in furniture. To get weighted average combine secondary processing and construction losses, multiply proportion in use times wood loss as percent of standing tree for construction and for furniture and sum. 0.76 * 0.03 + 0.24 * 0.12 = 5%. Volume remaining in end uses 23% - 5% = 18%.
Long-lived uses	Percentages in long-lived uses by primary product; total volume of each primary product produced in U.S. (McKeever 2002, PNW-GTR-524, Tables 18, 20, 22; Smith et al. 2006, GTR-NE-343, Table D2).	Primary products represented in GTR-343 and GTR-524 tables are representative of all primary solid wood products for United States, and same percentages in long-lived uses apply for exports/imports.	Multiply percent of softwood lumber used in construction or furniture (Smith et al. 2006, Table D2) times volume of softwood lumber produced in 1998 (McKeever 2002, Table 18). Repeat for hardwood lumber, softwood plywood, OSB, and nonstructural panels to derive amount in long-lived uses. Sum and divide by sum of total production to get weighted average percent in long-lived uses, 60%.
Use losses	Amount of U.S. production for each primary product for 1998 (McKeever 2002); percent of each primary product in each end use: single-family, multi-family, residential upkeep, and all other (Skog 2008); alternative in-use formulas (first-order for Smith et al. 2006, GTR-NE-343, and other examples from Miner 2006).		Alternative formulas were applied for a period of 100 years. Amount remaining is weighted average based on solid wood products in each end use in the United States from McKeever 2002, proportions of residential wood use in single-family and multi-family construction by primary product from Skog 2008, and unit conversions from Smith et al. 2006, Table D1. Table 2 reports lowest and highest losses over 100 years from alternative formulas. Medium loss listed in Table 2 is weighted average loss.
Comparison with 1605(b) loss estimates	North Central fraction of softwood pulp roundwood in use 0.008, in landfills 0.084. Pacific Northwest Westside fraction of softwood sawlog roundwood in use 0.130, in landfills 0.279 (Smith et al. 2006, Table 6).	See above for regional roundwood as percent of standing tree volume.	North Central softwood pulp fraction in use or landfills = 0.008 + 0.084 = 0.092. 0.084 / 0.092 = 91% in landfills. Percent of standing tree volume = 0.092 * 0.55 = 5%. Pacific Northwest Westside softwood sawlog fraction in use or landfills = 0.130 + 0.279 = 0.409. 0.279 / 0.409 = 68% in landfills. Percent of standing tree volume = 0.409 * 0.61 = 25%.
Methane emissions	23% of solid wood and 56% of paper decomposes in landfills (Skog et al. 2008). About 80% of carbon released from U.S. landfills is in the form of CO_2 — about 50% of C is released as methane but about 40% of methane is flared or burned for energy, which converts it to CO_2 (U.S. EPA 2006). GWP of methane is 25 (Forster et al. 2007).	Assume that portion of wood waste from mills and construction that is subject to decay (23%) completely decomposes by year 100.	Calculate net CO_2e emissions per ton of solid wood CO_2e deposited in landfills: 0.8 * 0.23 = 0.184 tons CO_2 and 0.2 * 0.23 * 12 / 44 * 16 / 12 = 0.0167 tons CH_4. CH_4 measured as CO_2e is 0.0167 * 25 GWP = 0.418. Total CO_2e released per ton solid wood landfilled is 0.184 tons CO_2 plus 0.418 tons CH_4 measured as CO_2e = 0.60 tons, so net long-term CO_2e storage is 40% of CO_2e deposited in landfill.

Data Appendix – Conversions and Calculations (continued)

Item	Original Data and Source	Assumptions	Computed Estimate
CO_2e from solid wood wastes remaining in use and in landfills at 100 years	Use medium range of wood losses from previous sections of this report. 67% of solid wood waste is disposed of in landfills and 77% of solid wood waste remains in landfills at 100 years (Skog et al. 2008). Net GHG emissions avoided are 40% of CO_2e in wood waste, due to methane effects (see methane calculations above).	Primary and secondary mill and construction waste is landfilled at typical rates (67%) and 23% of it decomposes by 100 years after tree is cut. House demolition waste is landfilled at a similar rate, but only 11.5% decomposes by year 100 since disposal occurs gradually over time.	Primary mill waste is about 13% of standing tree volume. Net CO_2e in landfilled mill waste at year 100 would be 0.13 * 0.67 * 0.40 = 3% of CO_2e in standing tree. Secondary mill/ construction waste is about 4% of standing tree volume. Net CO_2e in landfilled secondary mill/construction waste would be 0.04 * 0.67 * 0.40 = 1%. House demolition waste is about 17% of standing tree volume. Net CO_2e in house demolition waste (assuming 1/2 of decay-prone portion decomposes by year 100) would be 0.17 * 0.67 * 0.70 = 8%.
Fossil Energy and Other Process Emissions			

Ratios of logs:100-year C, lumber:100-year C, house wood: 100-year C	Wood remaining as percent of standing tree from previous section of this report using medium range estimates. Logs = 60%, Lumber = 23%, End products = 18%. 100-year wood (in use and landfilled) = 14%.	These ratios are used to convert emissions per mass of raw material to emissions per CO_2e of wood remaining in Year 100 (see rows below).	Ratios:
			logs:100-year wood = 60 / 14 = 4.3;
			lumber:100-year wood = 23 / 14 = 1.6;
			end products:100-year wood = 18 / 14 = 1.3.
			For CORRIM houses with 75-year life, all materials to landfill in year 75, 25 years decomposition in landfill leaves 81.75% of wood material remaining in year 100. So ratio is 18 / (18 * 0.8175) = 1.22.

Harvest	Fossil fuel emissions for site preparation and harvest operations for Southeast and PNW low- and high-intensity management range from 8.02 to 9.71 kg of CO_2 plus 0.00171 to 0.0127 kg CH_4 plus 0.00019 to 0.00554 kg N_2O per m^3 of log (Johnson et al. 2005).	1 m^3 of logs weighs about 525 kg. Multiply by 0.5 to estimate carbon content, multiply by 3.6667 to estimate CO_2 content. Hence logs contain 962 kg CO_2e per m^3.	Convert CH_4 to CO_2e by multiplying by 25, and N_2O to CO_2e by multiplying by 310 and total all GHGs per m^3 of log. Convert CO_2e per m^3 to CO_2e per kg by dividing by 962 kg/m^3. Totals range from 0.0085 to 0.0132 kg CO_2e of emissions per kg of CO_2e in log. Calculate ratios to 100-year carbon by multiplying by 4.3. Range from 0.04 to 0.06.
Harvest	Harvest emissions 11,411 CO_2e for 193,170 metric tons of C in logs (Gower et al. 2006).		Convert log C content to CO_2e content by multiplying by 3.6667 = 708,296 metric tons. Divide harvest emissions by log CO_2e = 0.02. Calculate ratio to 100-year carbon by multiplying by 4.3. Result is 0.07.
Primary manufacturing	Carbon content in raw logs and CO_2 and CH_4 emissions by product (Kline 2005, Tables 2 and 7; Milota et al. 2005, Tables 5 and 8; Wilson and Sakimoto 2005, Tables 12 and 13; Bergman and Bowe 2008, Tables 2 and 5).	Assume logs are 50% carbon.	Convert methane (minor emissions) to CO_2 equivalent by multiplying by 25. Sum fossil CO_2 and CH_4 as CO_2e. Estimate C in log by multiplying mass by 0.5, then multiply by 3.6667 to derive CO_2e in log. Divide emissions by raw log CO_2e to get ratios of 0.02 (softwood lumber South or Northeast hardwood), 0.04 (softwood lumber West), 0.03 (OSB), 0.005 (plywood). Including off-site emissions, 0.07 Northeast lumber, 0.18 OSB, 0.11 plywood. Calculate ratio to 100-year carbon by multiplying by 4.3. Range 0.02 to 0.77.
Primary manufacturing	Source reports fossil C emissions as percent of C in primary product (Liski et al. 2001).		0.032 sawmill, 0.069 plywood mill. Calculate ratio to 100-year carbon by multiplying by 1.6. Results 0.05 and 0.11.
Primary manufacturing	Sawmill nonrenewable emissions (lumber portion only) 4,708 metric tons. C stored in lumber = 31,705 (Home Depot) plus 50,477 (other) total tons (Gower et al. 2006).		Convert lumber C to CO_2e by multiplying by 3.6667 = 301,366. Divide sawmill emissions by log CO_2e = 0.02. Calculate ratio to 100-year carbon by multiplying by 4.3. Result is 0.07.

Data Appendix – Conversions and Calculations (continued)

Item	Original Data and Source	Assumptions	Computed Estimate
Primary manufacturing	200 kg CO_2e emissions per metric ton of panels (Skog 2008, p. 16).	1 metric ton panels contains 0.48 metric tons C (Smith et al. 2006, GTR-NE-343, Table D1 panel average).	1 * 0.48 * 3.6667 = 0.88 metric tons CO_2e in 1 metric ton of panels. 200kg = 0.2 metric tons CO_2e of emissions/metric ton panels. 0.2 / 0.88 = 0.23. Calculate ratio to 100-year carbon by multiplying by 1.6. Result is 0.36.
Primary manufacturing, construction, transportation	4-story wood-framed apartment building—wood content has 1,400 GJ embedded energy and primary manufacturing emissions are 117 tons CO_2e. Wood contains 15.8 MJ/kg energy content (Borjesson and Gustavson 2000).	Lumber is 50% carbon. Assume all wood embodied in house remains at 100 years.	1,400 GJ = 1,400,000 MJ. 1,400,000 / 15.8 = 88,608 kg of wood in building. 88,608 * 0.5 = 44,304 kg C in wood in building. 44,304 * 3.6667 = 162,449 kg CO_2e or 162 metric tons CO_2e in building wood. Fossil fuels used to produce and transport building materials emit 117 metric tons CO_2e. 117 / 162 = 0.72.
Primary manufacturing and transport	Average combined process and transportation energy and process non-energy emissions, virgin inputs (U.S. EPA 2006, Exhibit 2-2). Conversion factors by product for wet to dry tons (Exhibit 6-4) and carbon content as percent of dry matter (Exhibit 6-2).	Original units are metric tons carbon equivalent per wet (as delivered) short ton of product.	Convert wet tons of product to dry tons. Convert short dry tons to metric dry tons. Calculate carbon content. Calculate ratio of C in emissions to C in discarded material, 0.12 for lumber, 0.24 for fiberboard. Calculate ratio to 100-year carbon by multiplying by 1.3. Results 0.16 to 0.31.
Construction	Construction emissions for Minneapolis and Atlanta model houses converted to CO_2e 1,271 and 1,121 kg (Meil et al. 2004, Table 3-4). Wood as percent of materials 15% and 10% (Miel et al. 2004, Table 10). CO_2e content of homes at 22.4 and 17.1 metric tons (Perez-Garcia et al. 2005).	Estimate construction emissions for wood based on wood as portion of total materials. House life is assumed to be 75 years, so CO_2e remaining at 100 years reflects 25 years decomposition in landfill (82% remains in year 100).	Convert total construction emissions to GWP. Minneapolis house = 1.27 metric tons, Atlanta house = 1.12 metric tons. Proportionally, construction emissions would be 0.15 * 1.3 = 0.19 for Minneapolis and 0.1 * 1.1 = 0.11 for Atlanta. 82% of CO_2e remains at 100 years: 18 metric tons CO_2e for Minneapolis house and 14 for Atlanta house. Calculate ratio of construction emissions to 100-year CO_2e. 0.19 / 18 = 0.011 for the Minneapolis house and 0.11 / 14 = 0.008 for the Atlanta house.
Transport to construction site	Construction transport emissions converted to CO_2e 37 and 21 kg (Meil et al. 2004, Table 3-4). See above for other data.	Estimate transport emissions for wood based on wood as portion of total materials. House life is assumed to be 75 years, so CO_2e remaining at 100 years reflects 25 years decomposition in landfill (82% remains in year 100).	Convert total transport emissions from manufacturing to construction site to GWP. Minneapolis house = 0.037 metric tons CO_2e; Atlanta house = 0.021 metric tons CO_2e. Estimated wood transport for Minneapolis = 0.15 * 0.037 = 0.006; Atlanta = 0.10 * 0.021 = 0.002. Construction wood transport emissions as percent of 100-year wood carbon storage is insignificant.
Transport to end use	128,199 (Home Depot) + 83,396 (other) total tons CO_2e transport emissions (Gower et al. 2006).	Logs are 50% carbon.	Total carbon stored in lumber 31,705 + 50,477 = 82,182. 82,182 * 3.6667 = 301,337 tons CO_2e in lumber . Total transport emissions = 128,199 + 83,396 = 211,595. Divide transport emissions by lumber CO_2e 211,595 / 301,337 = 0.70. Calculate ratio to 100-year carbon by multiplying by 1.6. Result is 1.12.
House maintenance	Emissions associated with maintenance of wood components 1,066 and 890 kg CO_2e (Winistorfer et al. 2005, Tables 8 and 9). For total wood CO_2e in house see above.		Divide maintenance CO_2e by 100-year CO_2e (see above). 1.066 / 18 = 0.06 and 0.890 / 14 = 0.06.
Demolition	435 and 491 kg CO_2e demolition energy emissions (Winistorfer et al. 2005, Table 11). For total wood CO_2e in house see above.		Multiply total demolition CO_2e by fraction of landfilled material that is wood. 435 * 0.15 = 65 kg. 491 * 0.10 = 49 kg. Divide estimated wood demolition CO_2e by house content CO_2e. 65 / 22,400 = 0.003 and 49 / 17,400 = 0.003.

COVER PHOTOS:
Top: Photo courtesy of Terry Brown,
Oregon State University

Left: Photo by Ann Ingerson

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